MAR 19 1956

STACKS

JET PROPULSION

Journal of the
AMERICAN ROCKET SOCIETY
Rocketry . . . . Jet Propulsion Sciences . . . . Astronautics

VOLUME 26 MARCH 1956 SCIENCE AND TECHNOLOGY NUMBER 3

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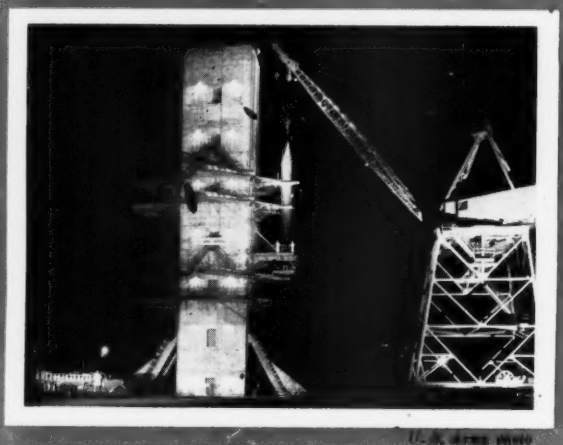

U. S. Army photo

Ballistic missile REDSTONE is lifted into place on Army Ballistic Missile Agency's new static test stand

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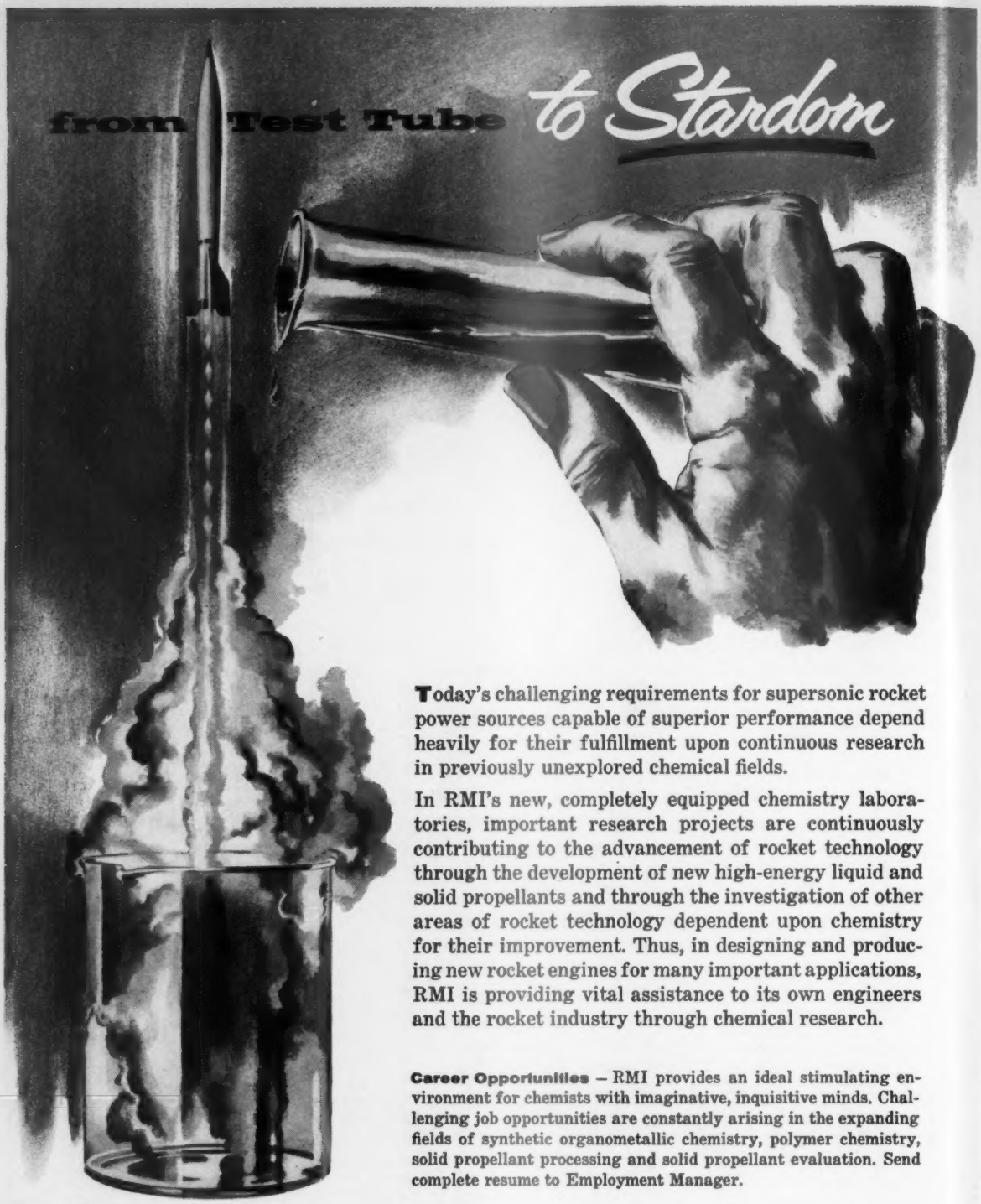

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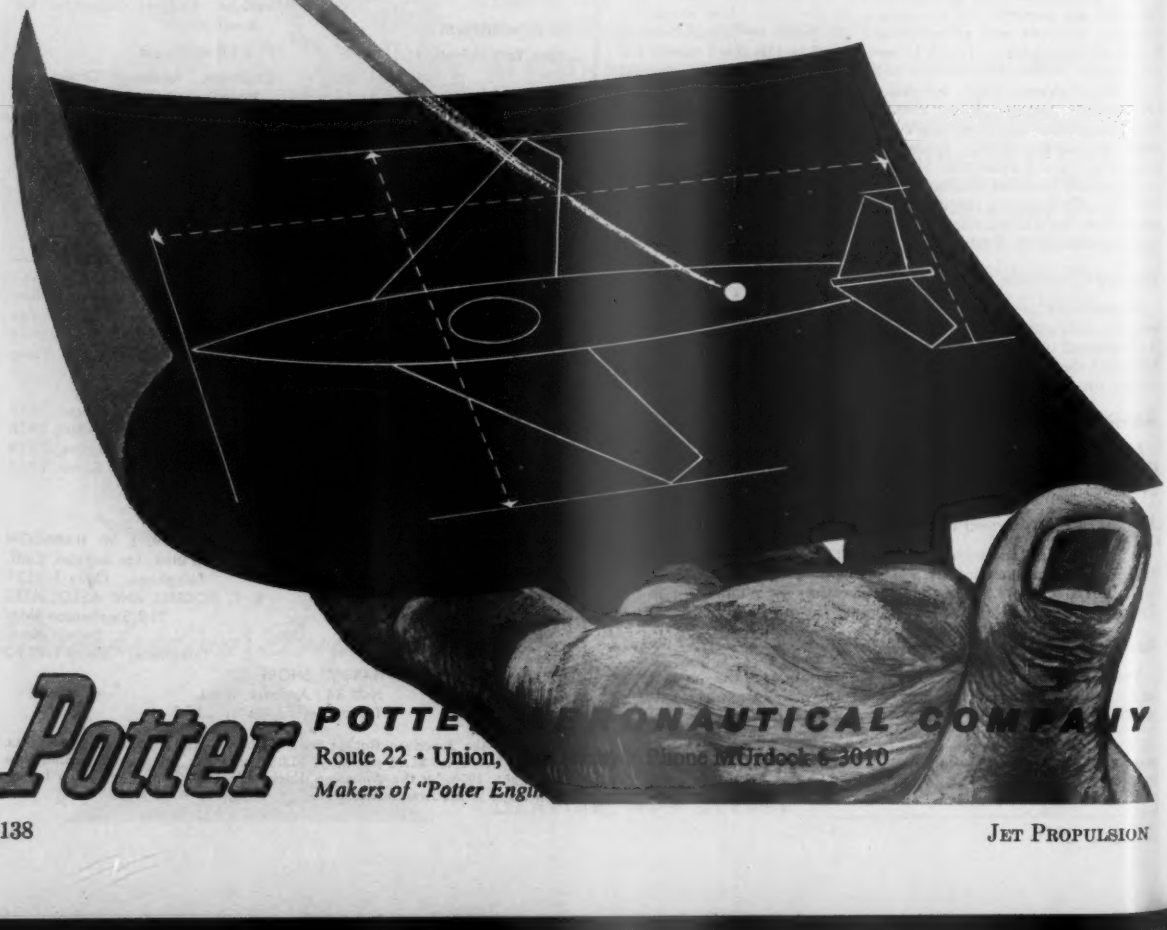

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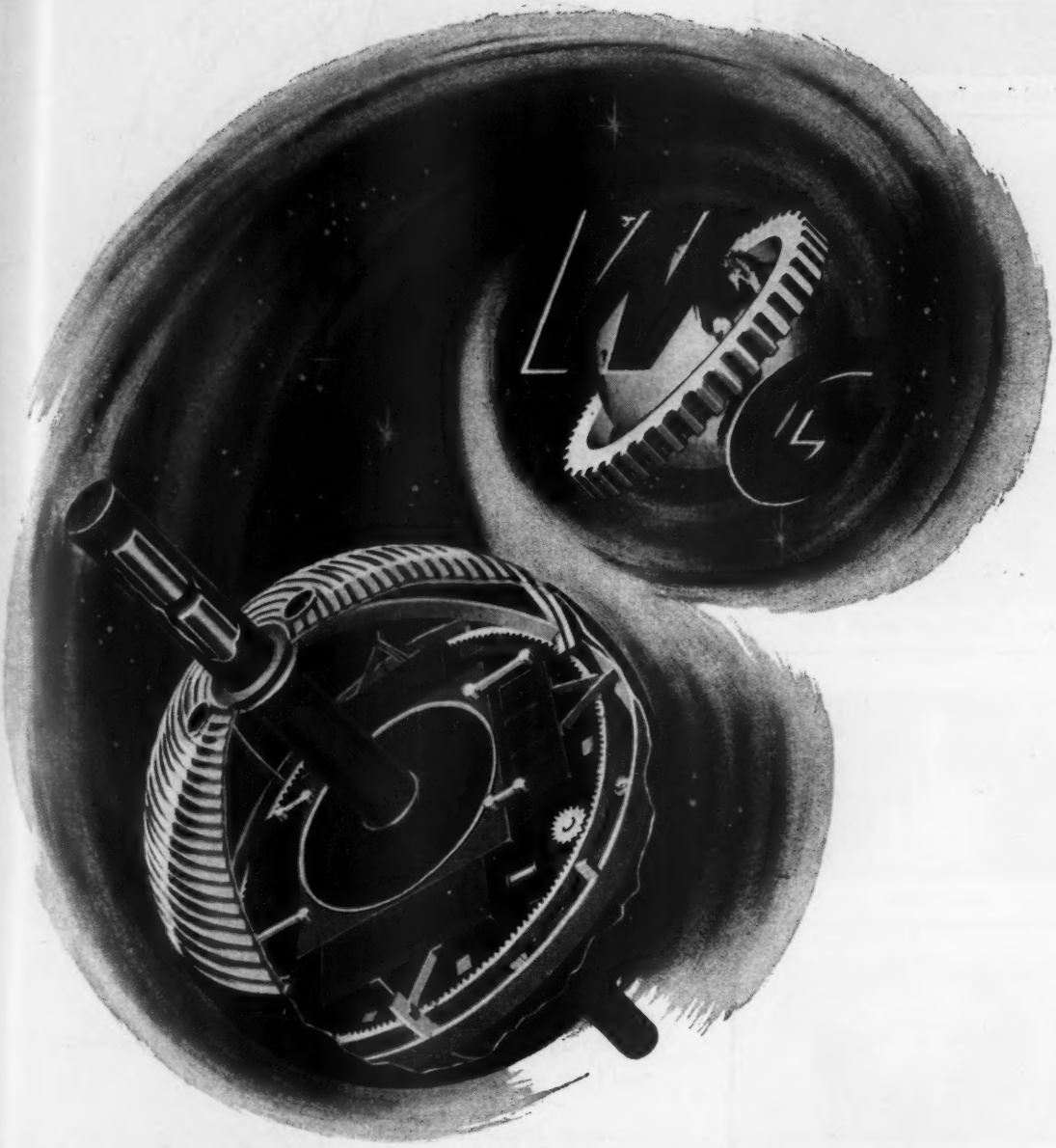

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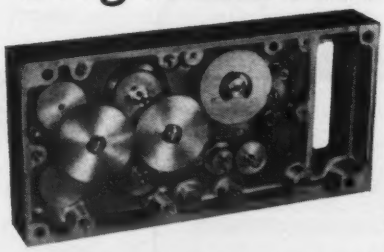

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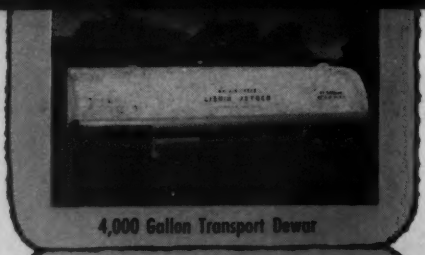

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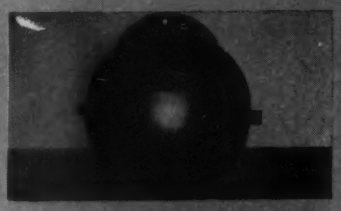

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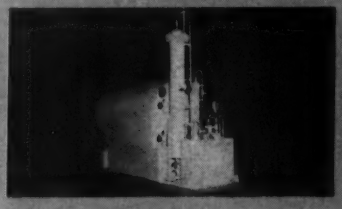

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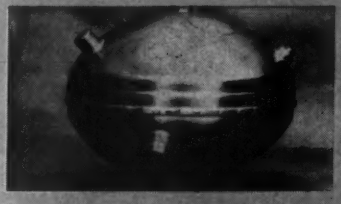

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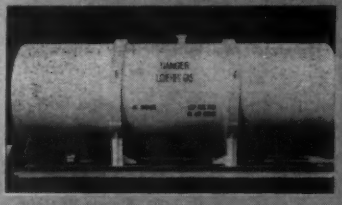

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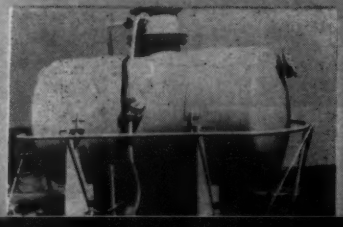

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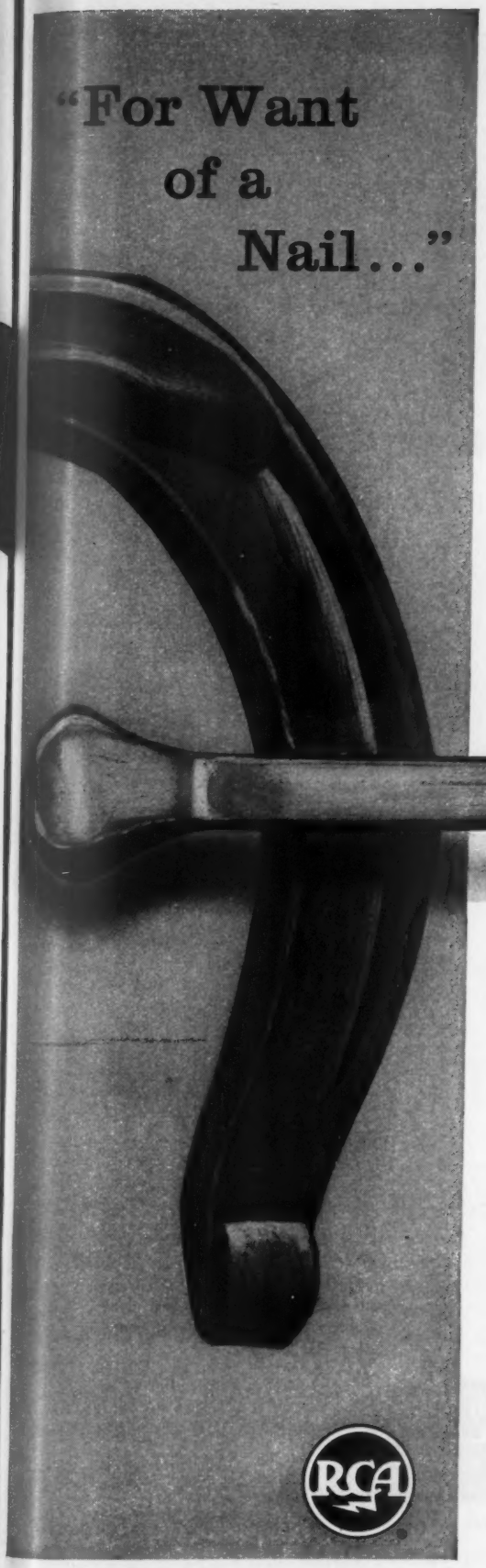

For want of a nail the shoe is lost,
for want of a shoe the horse is lost,
for want of a horse the rider is lost.

George Herbert's statement applies to electronics today as it did to riders three centuries ago. The point may be illustrated by considering a vital electronic unit made up of thousands of components. If the least of these components fails, the whole unit may fail—and with it a strategic military mission.

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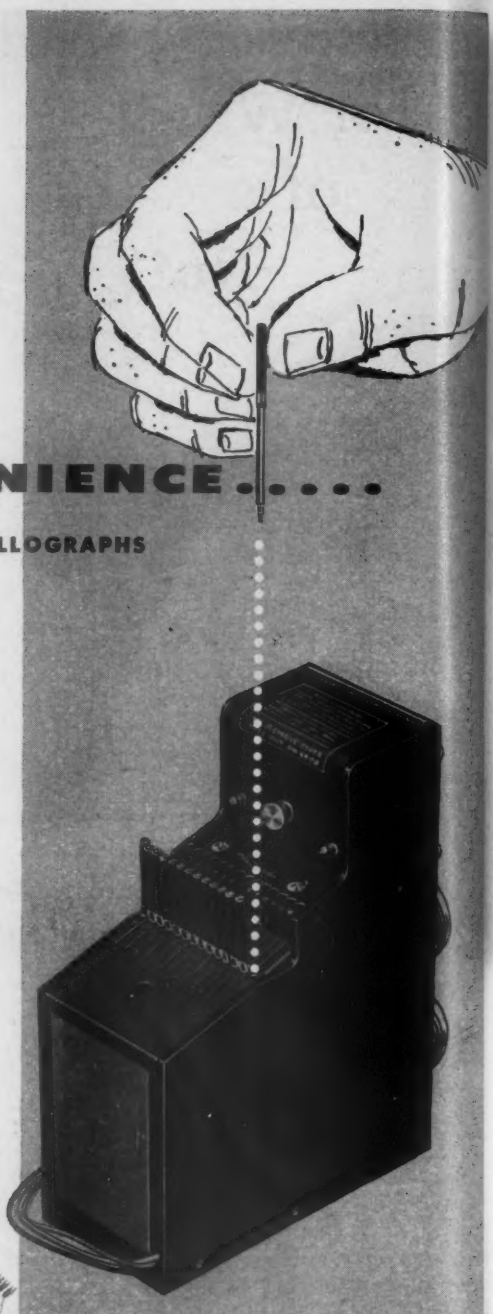

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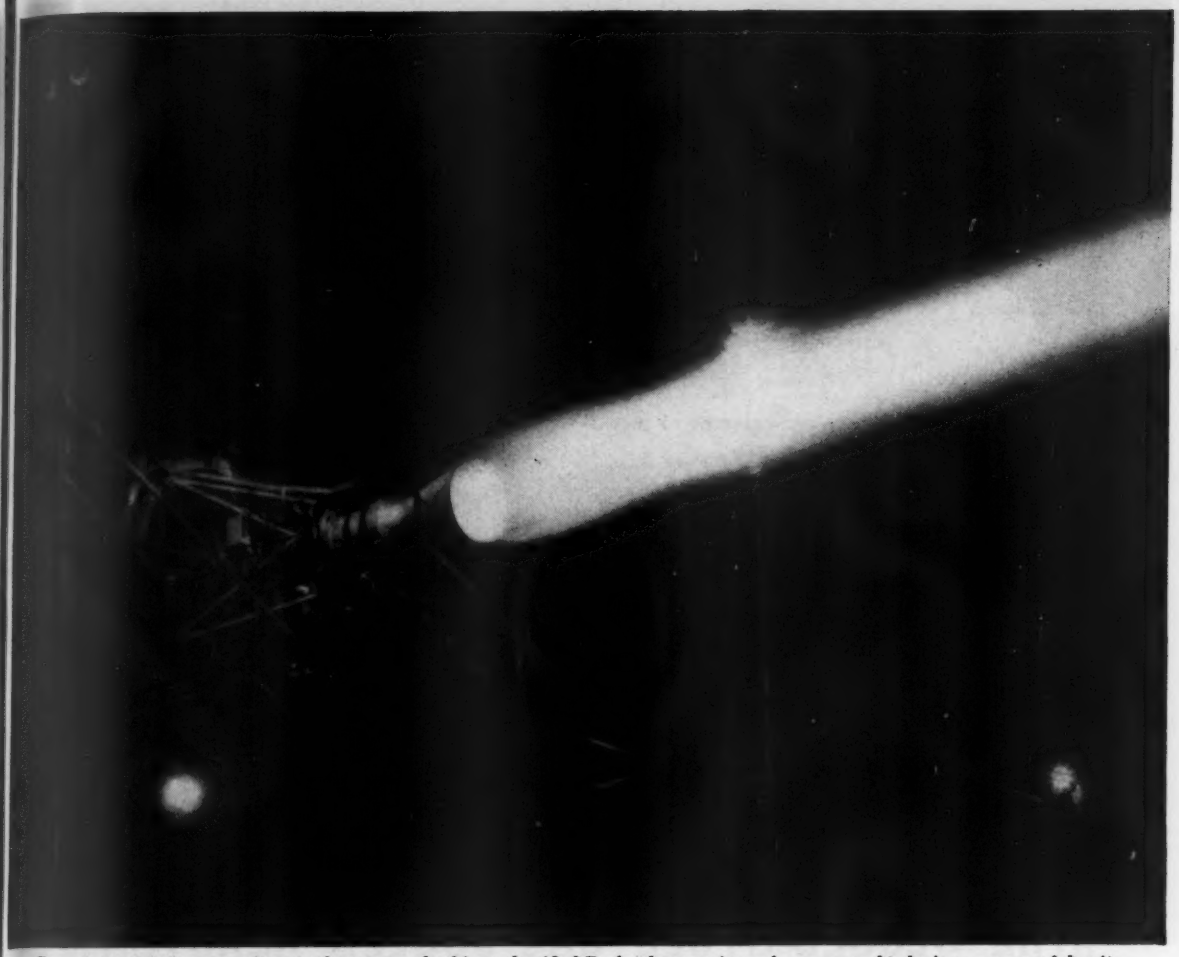

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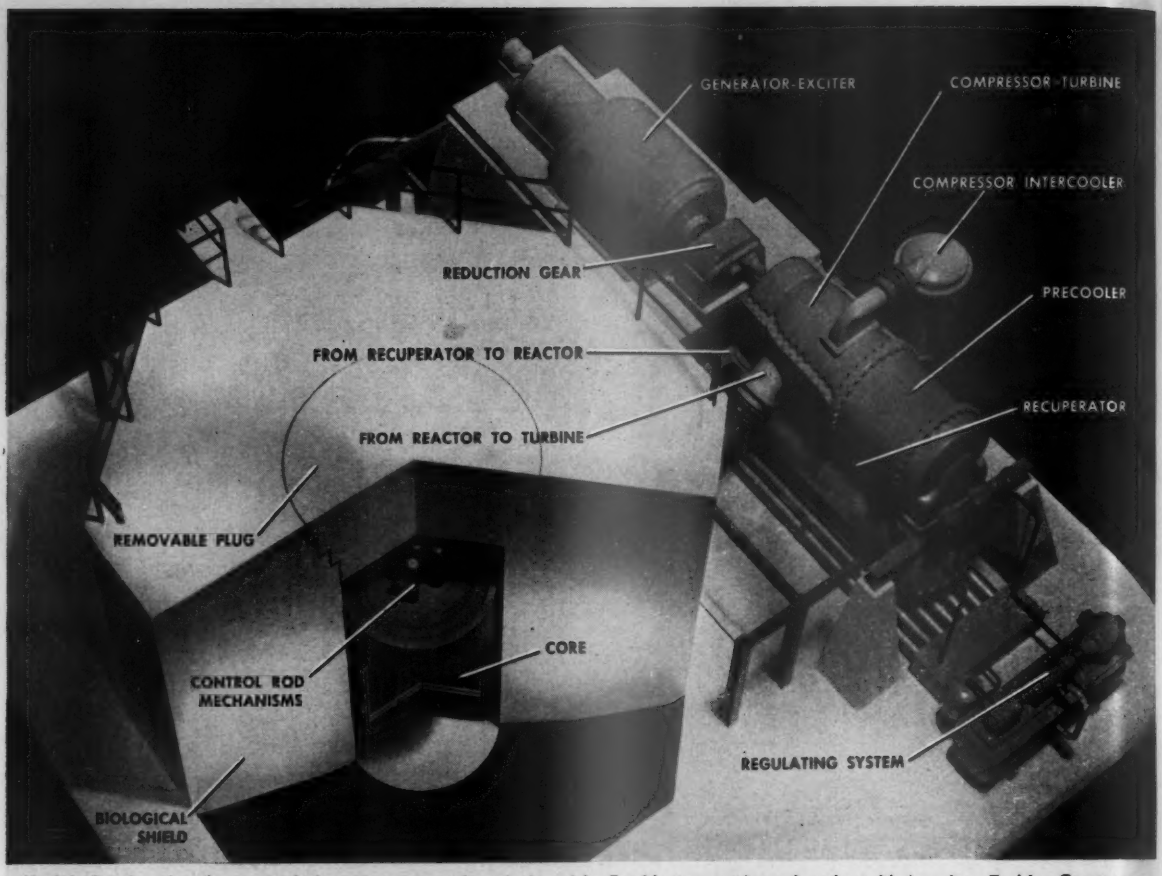

Model of a closed-cycle gas-cooled reactor power plant designed by Ford Instrument in conjunction with American Turbine Company.

THE CLOSED-CYCLE GAS-COOLED REACTOR ... a progress report from Ford Instrument

What Is It? The Closed-Cycle Gas-Cooled Reactor is a reactor whose principle of operation is based on the concept of the use of a gas under pressure as the working fluid for *direct* transfer of energy from the reactor to a turbine. The gas used is nitrogen, carbon dioxide or helium. The closest analogous commonly known reactor type is the "boiling water" reactor.

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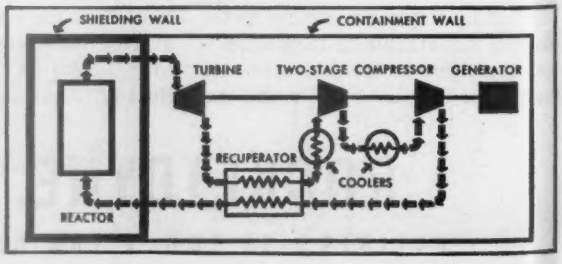
5. *Maximum* safety. The nature of the working fluid used, with its freedom from phase change, means that provisions for containment in the event of an "incident" are simple, and that protection against incidents is simultaneously enhanced. The closed-cycle design precludes contamination of the atmosphere.
6. *A minimum* of moving parts. In this design, pumping power is provided by a turbo-compressor set, and no other pumps are required.

For more information on this new type of reactor write Ford Instrument Company.

A SCHEMATIC OF THE CLOSED-CYCLE GAS-COOLED REACTOR



101

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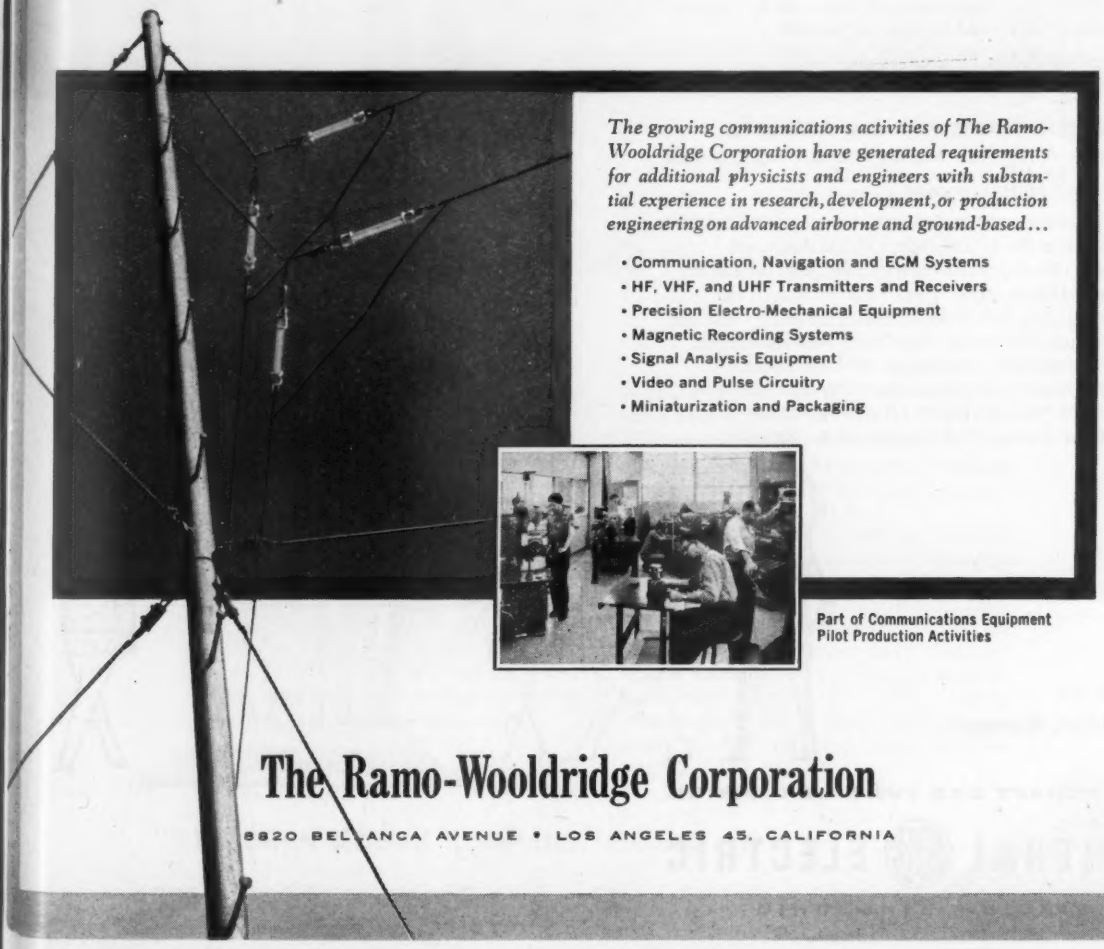
ADVANCED Communications

The design of modern communications equipment involves much more than electronic circuit techniques. Keyboards and coders are often required to translate the intelligence to be transmitted into "machine language." Recording and reproducing devices store intelligence until the equipment is ready to transmit it, or hold received intelligence until it can be translated back into human language by a printer or other output display device.

The combination of such mechanical and electromechanical techniques with the better known but still developing techniques of electronic circuit design makes of modern communications a much broader field than is commonly recognized. When such technical tools are used to provide equipment tailored to our rapidly improving understanding of propagation phenomena and information theory, the resulting practical improvements in communication are sometimes little short of spectacular.



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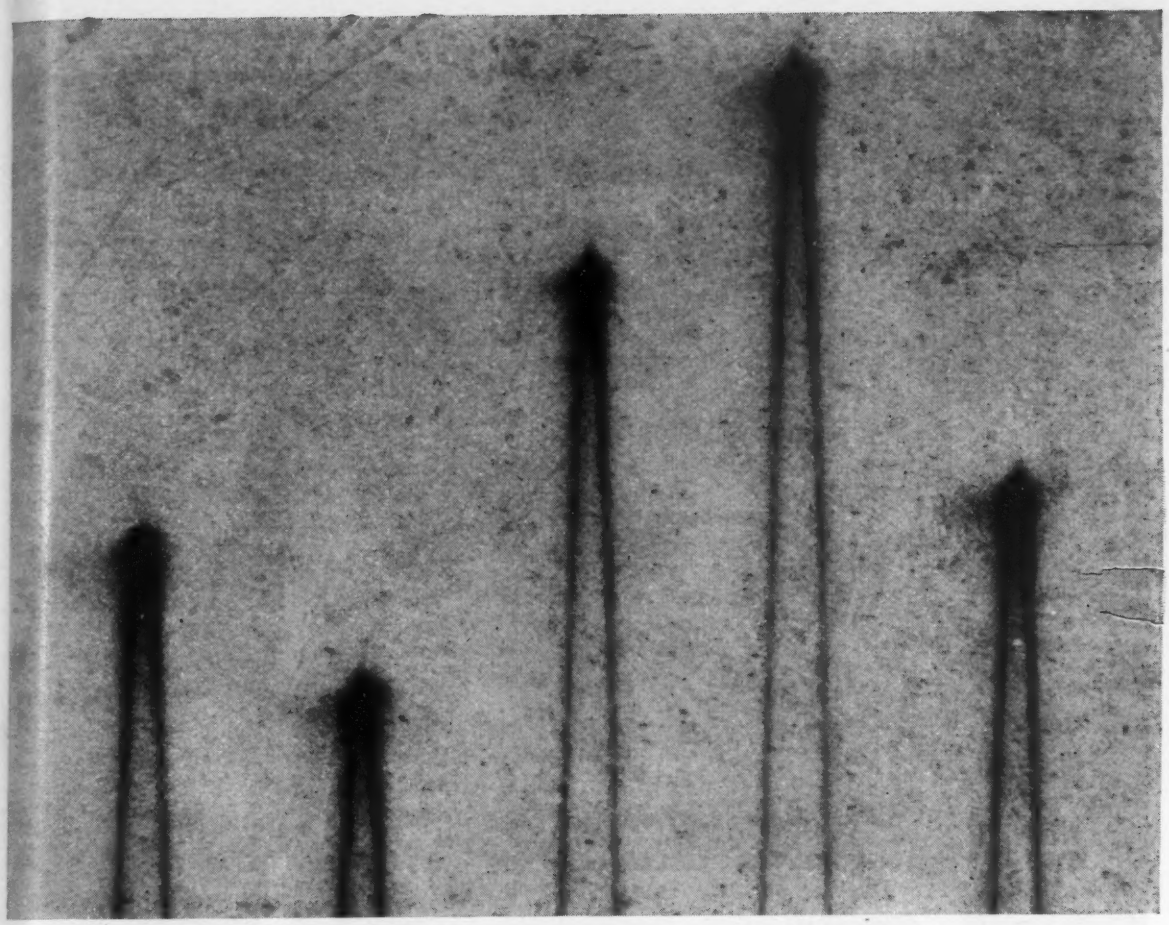

20× photomicrograph of high-spot-velocity trace on Kodak Linagraph 1344 Paper.

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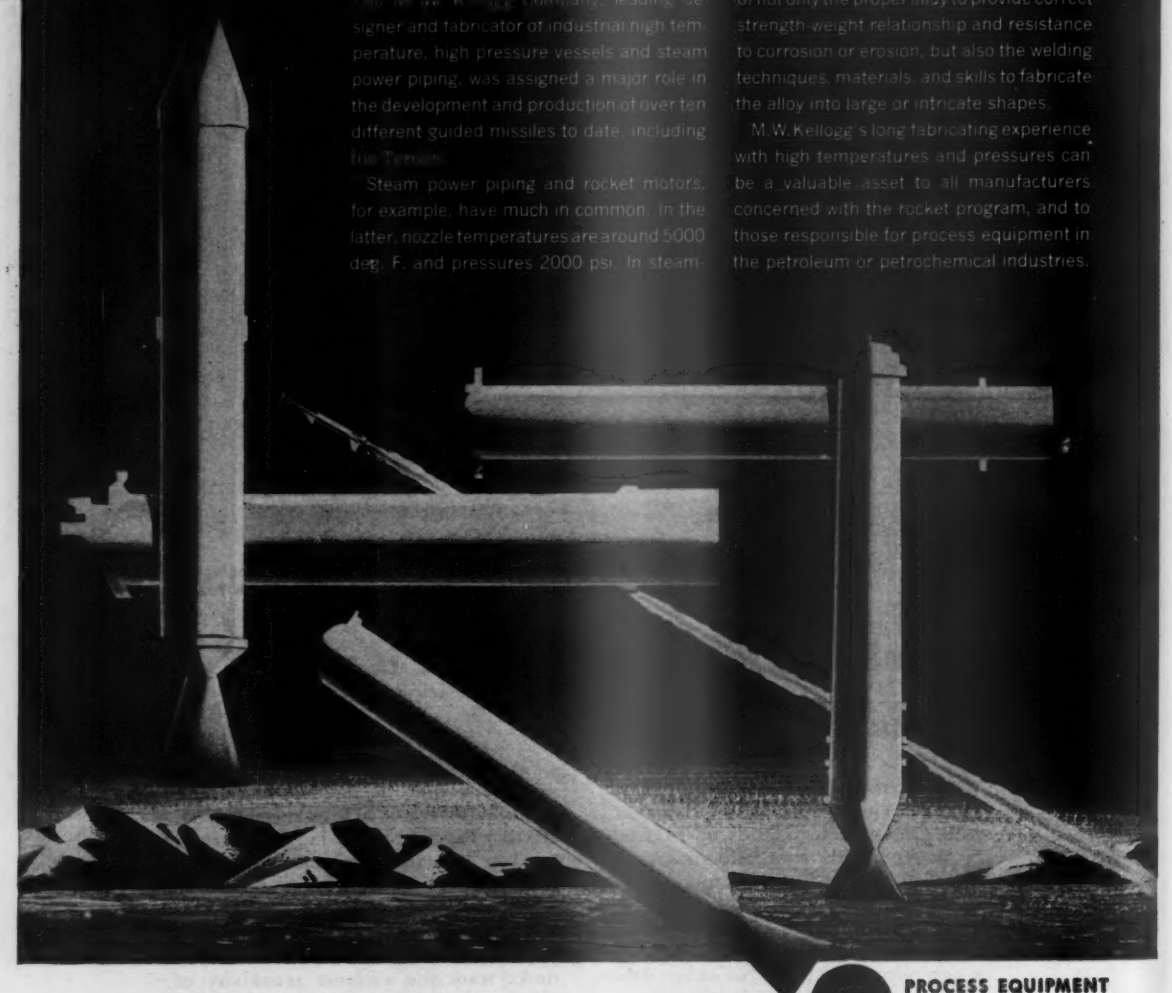

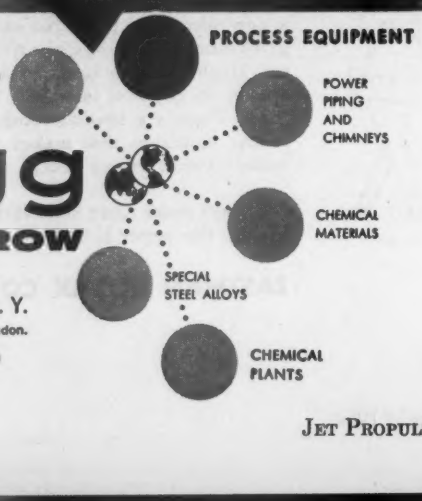

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Some New Metallurgical Processes of Interest in the Field of High Speed Flight

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In the field of high speed flight, the need to obtain materials for extremely high temperature service has stimulated the development of several new metallurgical processes now used to investigate the high melting point metals, such as tungsten, molybdenum, and chromium. Some of these processes are described, and the resulting alloys obtained or expected from them discussed and compared with the high temperature alloys available today. The potentialities and limitations of new alloys based on these metals are outlined.

Introduction

THE advent of gas turbine, ramjet, and rocket propulsion systems has created a demand on the metallurgist for metallic materials having properties which he has been hard pressed to meet. His progress in coping with these new requirements has been hampered by several conditions. Because metallurgy is so old, it has most often been approached as an art, rather than as a science, and until recently, little fundamental work has been done in the field. Furthermore, in the past there was little incentive to improve metallurgical products because there has been no great need for it. Finally, because of the large and costly plant tooling required for most basic metal industries, major changes in products, or the processes to produce them, were, and still are, extremely expensive. This has been particularly true since, unlike the chemical industry, for example, the metallurgical field boasted virtually no pilot plants to evaluate new products and processes on a less expensive, semicommercial scale.

However, the phenomenal progress which we have witnessed in several fields of engineering—electronics, high speed flight, nuclear physics, and others—has suddenly required the services of alloys with properties unheard of in the past. It is fortunate that considerable basic metallurgical research, mainly accomplished in the past 15-year period has helped provide these materials or point the way to their eventual manufacture. As a result, it is probable that we are on the verge of a new era which will manifest itself in a rash of alloys, strange to us now, but with the unique properties required for several different applications. Most of these new alloys will require processing techniques not formerly employed or considered practical, and it is in part this fact which is forcing the appearance, finally, of several pilot plants.

It is the purpose of this paper to describe some of the new processes being developed in an attempt to produce these alloys in wrought form, and outline in a brief way the results obtained or expected from them. In pointing out the problems involved and the methods used to circumvent them, it is hoped that those who are concerned with materials in the jet propulsion field may gain a better understanding of capabilities and limitations of alloy systems. It is also hoped that some insight into the potentialities of new alloys may be gleaned to guide future planning. It may further result that some may see new applications immediately for some of these recent process developments.

It will not be the intent of this presentation, however, to provide up-to-the-minute data on commercial alloys, which are available from numerous investigators and manufacturers' literature. Data, where given, are only typical and used to illustrate the capability of a process.

The metals which have hitherto been the building blocks of our commercial alloys, iron, copper, aluminum, and magnesium, gained their early pre-eminence for several reasons. They were plentiful in the earth's crust, and their ores were in some cases quite easily reduced in order to win the relatively pure metal required to form the final alloy. They and their alloys had only moderately high melting points, therefore were easily melted with minimum contamination from air. Finally, their castability and workability were excellent, permitting the formation of products of almost any desired shape. Some of the other metals with which we are familiar, manganese, zinc, tin, chromium, nickel, cobalt, molybdenum, tungsten, vanadium, etc., were not considered as the bases for alloy systems, but rather as the alloying elements added to iron, copper, aluminum, or magnesium, to enhance their fundamental properties. But these latter metals, and some of the foregoing alloying elements, have low melting points, which though an asset in their production, places a very severe limitation upon their service at elevated temperatures. Hence, in the field of high speed flight, whether in gas turbines, ramjets, or rockets, it is inevitable that the requirement for higher operating temperatures will render useless the alloys based on iron, or even nickel and cobalt, the best "super alloys" available today. The service temperatures of these alloys for appreciable lengths of time will probably be limited to 1600–1800°F.

It is natural in seeking the metals on which to base new alloys for higher temperature service, to choose those with the highest melting points, since this property is a rough index of their high temperature useful strength. Table 1 lists the stable metals of known melting points in decreasing order of their melting temperatures down to about 2600°F. Note that iron, nickel, and cobalt, the bases for virtually all high temperature alloys at the present, melt at 2800°F or below. On the other hand, there are more than a dozen metals with higher melting points, up to tungsten at 6170°F, while at least half of these melt above 4000°F. Although it is of no fundamental significance, in one column is also shown the melting point to density ratio, which, lacking any actual

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Table 1 Melting points and other physical properties of the high melting metals

	Atomic no.	Melt'g point	Density #/cu. in.	M.P./Den. $\times 10^3$	Specific heat	Coefficient of exp.	Thermal conduc'ty	Modulus
Tungsten	74	6170	0.697	8.8	0.032	4.3	0.48	50
Rhenium	75	5740	0.72	8.0	0.033			
Tantalum	73	5425	0.60	9.0	0.036	6.5	0.13	27
Osmium	76	4900	0.813	6.0	0.031	4.6		80
Molybdenum	42	4760	0.369	12.9	0.061	4.9	0.35	50
Ruthenium	44	4500	0.441	10.2	0.057	9.1		60
Iridium	77	4449	0.813	5.5	0.031	6.8	0.14	75
Columbium	41	4380	0.310	14.1	0.065	7.1		
Rhodium	45	3571	0.449	7.9	0.059	8.3	0.21	42
Chromium	24	3430	0.260	13.2	0.11	6.2	0.16	36
Zirconium	40	3365	0.230	14.6	0.066	5.0		11
Thorium	90	3300	0.415	7.9	0.034	11.1		
Platinum	78	3224	0.775	4.2	0.032	8.9	0.17	21
Titanium	22	3140	0.164	19.2	0.126	8.5		17
Vanadium	23	3100	0.217	14.2	0.120	7.8		
Hafnium	72	3100	0.412	7.5				
Palladium	46	2829	0.434	6.5	0.058	11.8	0.17	17
Iron	26	2802	0.284	9.9	0.11	11.7	0.18	28
Cobalt	27	2723	0.320	8.5	0.099	12.3	0.17	30
Yttrium	39	2700	0.199	13.5				
Nickel	28	2651	0.322	8.2	0.105	13.3	0.22	30

strength data on some of the metals, might be a crude indication at elevated temperatures of their strength to weight ratio. It is interesting to note that on this somewhat arbitrary index titanium registers well above all other metals and, of course, has recently gained considerable importance at moderately elevated temperatures. However, its relatively low melting point, only slightly above 3000°F, limits its likely range of use. Following next in order of their melting point to density ratios are vanadium, columbium, zirconium, yttrium, chromium, and molybdenum. However, vanadium, columbium, zirconium, and yttrium probably do not hold sufficient promise either because of their scarcity or only moderately high melting points.

Although their indexes are not as favorable, the extremely high melting points of tungsten, rhenium, tantalum, osmium, ruthenium, and iridium suggest that they, too, should be explored as base elements for future high temperature alloys. Unfortunately, it is likely that all but tungsten must be abandoned, at least temporarily, due to poor availability.

One word of caution should be injected at this point. Although the melting point of a metal may be a crude index of its elevated temperature strength, pure metals never have outstanding strength, which must be obtained by working, or alloying, for example, to produce stable high temperature precipitates. At the present state of the art, there is no reliable way to predict the specific alloy combinations which will provide high temperature strength. This, incidentally, may explain why titanium has not lived up to original expectations as a base for a truly high temperature alloy but has shown promise only at moderately elevated temperatures, below 1000°F. It may simply be that proper alloying to obtain maximum elevated temperature strength has not been evolved.

For successful high temperature use, there are, of course, many other properties of great importance, such as the modulus of elasticity, thermal conductivity, specific heat, coefficient of expansion, oxidation resistance, corrosion resistance, and crystallographic structure. It is beyond the scope of this paper to discuss these in any detail; however, a few general remarks should be made. Most of the high melting metals react very rapidly with oxygen, nitrogen, and carbon, which, it will be shown subsequently, create major problems in processing. Moreover, the oxides are not adherent and protective, as with aluminum; hence oxidation resistance is poor. This is a problem which cannot be fully covered here; suffice it to say that either by alloying, which seems unfavorable at the moment, or by protective coatings, these metals must be made corrosion resistant before they can be successfully employed. Favorable properties are low expansion coefficients, high moduli of elasticity, and good crystallographic structures, while high thermal conductivity and low specific heat are useful or troublesome, depending on the application.

Taking all factors into consideration, there appear to be three metals—tungsten, molybdenum, and chromium—which offer hope of very high temperature service. Since the first step in manufacturing alloys for these metals involves the necessity for melting them in order to produce wrought products, one is immediately faced with the problem that no known refractories can contain them. Their affinity for oxygen at their high melting points dictates they would react rapidly with the oxides of aluminum, silicon, and magnesium, which are the best crucible materials generally available. Furthermore, during melting, they must be protected from air for the same reason; hence must be melted in vacuum or an inert atmosphere, such as argon or helium.

Therefore, although greatest hope for higher operating temperatures rests primarily on these metals, they pose such formidable problems that the metallurgist first turned back to the present super alloys, based on iron, nickel and cobalt, to re-examine them and verify that the ultimate from them had really been achieved. Actually, as it turns out, a little higher service temperature may be squeezed out and, at the same temperatures, it appears likely that better performance can be realized. One method by which the latter can be accomplished is to melt in such a way as to yield a cleaner product.

New Melting Processes

Although most of today's super alloys are arc or induction melted under what formerly was considered clean and precisely controlled conditions, the fact is that some of their property limitations can be attributed to dirt, nonmetallic inclusions, trace element impurities, or gases incurred during melting. In an attempt to circumvent these limitations, considerable attention has been directed, in the past few years, to vacuum melting (1, 2, 3).[2]

Referring to Figs. 1 and 2, the technique consists simply of placing an induction furnace in a chamber which can be pumped down to the low micron range. Sufficient space is provided in the chamber to permit tilting the fur-

[2] Numbers in parentheses indicate References at end of paper.

nace to pour into one or more ingot molds situated below it, and gadgetry is added which allows the operator to charge the furnace, make minor additions, take temperature readings, etc., by remote control. Furthermore, the process can be made semicontinuous by the addition of valves or locks which permit the introduction of new charges and removal of previously cast ingots without opening the chamber and re-evacuating.

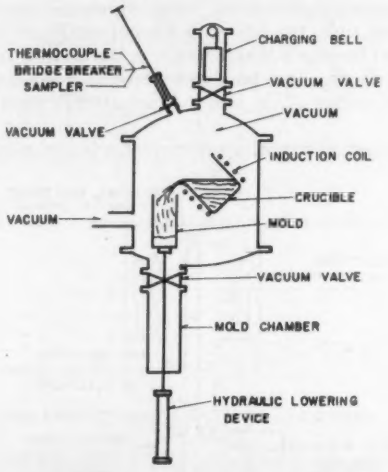

Fig. 1 **Schematic diagram of vacuum induction melting furnace**

Fig. 2 **Photograph of 1000-lb vacuum induction melting furnace and pumping system**

The basic advantages of the method are exclusion of air, which constitutes a major source of contamination in normal melting furnaces, and the ability, at the low pressures involved, to make certain refining reactions take place which are difficult or impossible to achieve at atmospheric pressure. Moreover, over-all yields are extremely high, since the cleanliness of the products obviates the necessity for much of the conditioning required on air melted alloys. In some cases, vacuum melting has permitted the utilization of much higher quantities of revert scrap in the charges than was possible in air melting. The technique has resulted in much closer control of analysis, since the variable oxidation of different metals in the charge, which accompanies air melting, is eliminated. One further advantage of vacuum melting must be considered. There are many alloy compositions which contain such high percentages of titanium or aluminum for precipitation hardening or oxidation resistance purposes that

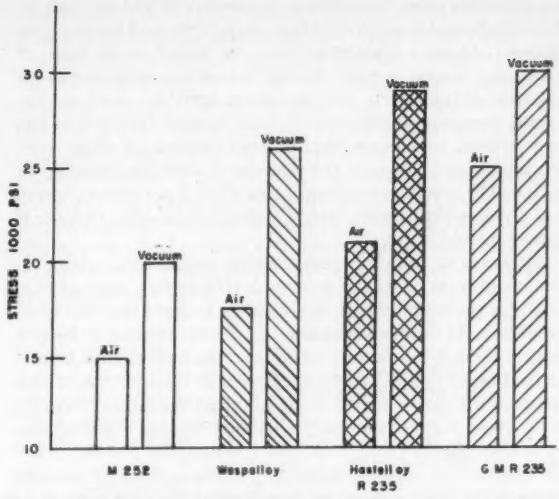

Fig. 3 **1000-hr rupture strength for air and vacuum melted high temperature alloys**

they cannot be satisfactorily worked if they are air melted. Typical examples are the high aluminum-iron alloys of the Alfenol (4) and Thermenol (5) type which are currently being investigated because of their great potential for high temperature service. To date these alloys have had to be melted in vacuo or inert atmospheres in order that they could be forged or rolled.

Fig. 3 illustrates the increase in rupture strength obtained by vacuum melting several commercial high temperature alloys, an improvement which may be as high as 40 per cent. Although it is not shown, the ductility of these alloys shows a similar increase when vacuum melting is employed. The enhancement of both strength and ductility can be attributed to the fact that vacuum melting eliminates many of the impurities, in the form of inclusions or gases, which collect at grain boundaries forming weak, brittle areas which initiate failure prematurely. However, even more improvement in properties can be obtained by vacuum melting than indicated in Fig. 3.

Fig. 4 shows how strengthening has been accomplished by composition changes in vacuum melted alloys which are not feasible in air-melted material. In the case of M 252, not only has vacuum melting alone increased rupture strength by about 30 per cent, the elimination of manganese and silicon has added at least another 10 per cent to the strength. These

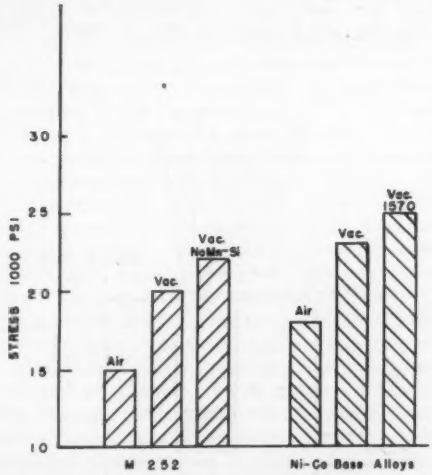

Fig. 4 **1000-hr rupture strength vs. melting practice for high temperature alloys**

two elements must be added to air melted M 252 in order to obtain sufficient ductility for both forgability and service conditions. Another illustration may be found in the case of 1570 alloy versus normal air and vacuum-melted nickel-cobalt base alloys. Here, the increase in ductility which accompanies vacuum-melting normal nickel-cobalt base alloys has been utilized to increase the hardener content, at some sacrifice in ductility, to gain the additional strength obtained in 1570. The hardener content of this alloy, 7 per cent tungsten and 4 per cent titanium, would make it impossible to forge if it were melted in air.

Although to date vacuum melting has been practiced in this country on heats not exceeding 1000 lb and often at considerable premium in cost, it should be realized that the technique is in its commercial infancy. There is reason to believe that in the not too distant future vacuum melting will be performed on as large a scale as is presently used for many high temperature alloys melted in air, and that the improvement in yield alone might eventually eliminate the price differential. It is also possible that with many alloys, the less expensive alternatives of melting under inert atmospheres or melting some of the raw materials in vacuum and the final alloy in air may prove to be adequate. It should not be overlooked that virtually anything that can be done with air melting can also be accomplished in vacuum. For example, centrifugal casting in vacuum has already been successfully practiced.

A modified vacuum technique which has recently come into use in Germany is known as vacuum casting (6). In this practice (Fig. 5) melting is conducted in air by conventional means, but the heat is teemed from the ladle into a mold which is situated in an evacuated chamber. Numerous schemes can be devised to seal the nozzle of the ladle to the chamber in order to prevent leakage of air into the chamber during teeming. Because of the low pressures attained, the stream from the ladle is broken up into fine particles and dissolved gases, such as hydrogen, are readily evolved from the molten metal. Hydrogen contents as low as one to two parts per million have been attained in ingots which have been vacuum cast. The results have been cleaner heats than normally obtained, with greatly improved properties. Although to date the practice has been used primarily as a means of removing hydrogen which leads to "flaking" in large rotor forgings, it is possible the principle may be applied to other alloys as well to promote cleanliness and improvement in ductility. One reason for mentioning the process is to illustrate on how large a scale vacuum techniques have already been commercially employed. In Germany, vacuum casting has been regularly practiced for about two years on heats weighing up to 150 tons.

Having initiated his vacuum techniques on the available super alloys, the metallurgist nevertheless had to face up to the fact that the need for alloys to serve at 1800°F and above

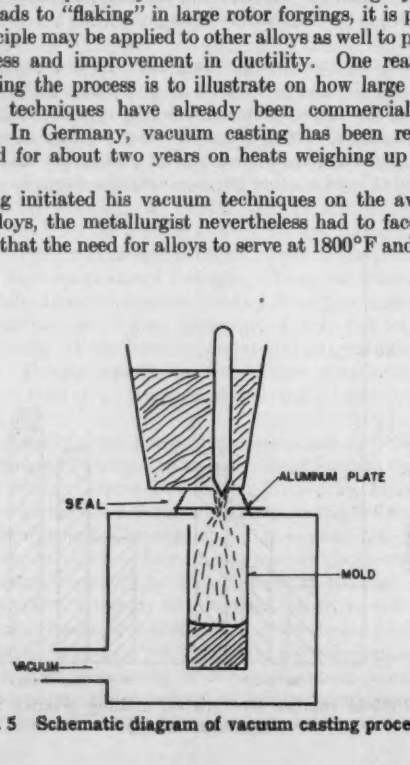

Fig. 5 Schematic diagram of vacuum casting process

was still uncomfortably close. Reluctantly, and with, to date, not sufficient quantity of effort, he returned to the problem of producing what may be called the "ultimate" alloys. As mentioned previously, the first problem again occurred in melting, where it has been established that no commercial refractory is adequate to the task. Fortunately, a new melting technique which has already been successfully employed on titanium and zirconium alloys, with minor modifications, has promised a way out of the dilemma of how to melt tungsten, molybdenum, and chromium base alloys. At the same time, the process is fundamentally so simple, it promises to become a major factor in the melting of a wide variety of alloys. It is familiar to most as cold hearth melting or arc casting (7, 8) and is schematically illustrated in Fig. 6.

In this method the refractory problem is circumvented by

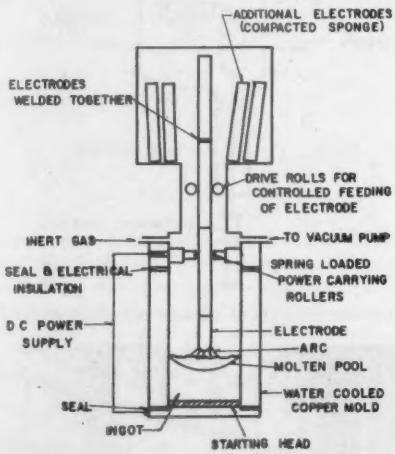

Fig. 6 Schematic diagram of cold hearth melting furnace

the use of a water-cooled copper cylinder, which serves both as the melting crucible and the ingot mold. The raw material must first be compacted into an electrode, which is gradually fed into the furnace as it melts off due to the arc struck between it and the molten bath. Due to water cooling of the mold, the ingot solidifies rapidly, which incidentally tends to minimize lateral segregation, and the molten pool rises as the electrode is fed in and melts off. It is possible to avoid compacting the raw material and feed it into the bath in granular or chunk form, using a water-cooled tungsten-tipped electrode, which does not melt off. However, some contamination of the molten bath from the electrode usually makes the method impractical. It is also usual practice to double melt, using the first ingot as the consumable electrode in a larger, second remelt furnace. The second melting is employed to homogenize the first melt ingot, which generally exhibits inadequate uniformity of alloying elements.

To demonstrate the potentiality of the arc casting process, Fig. 7 plots the short-time tensile properties of a variety of alloys versus testing temperature. At higher temperatures, short-time tensile properties are dependent to a large extent upon the strain rate, which is not known for all the data shown but is probably about 0.1 inch per inch per minute. It should be noted that the strength of the conventional cast or wrought super alloys begins to decline rapidly between 1200°F and 1600°F. Commercially pure, recrystallized molybdenum, on the other hand, exhibits a relatively small loss of strength beyond 1600°F, although the strength level is low (9). However, stress-relieved molybdenum base alloys show excellent tensile properties (10) comparable to the best super alloys, at 1600°F, and it is very probable they would retain a large proportion of their strength at 2000°F, if not beyond. The curve for cold-drawn tungsten wire has been added merely to show the excellent high temperature strength which can be

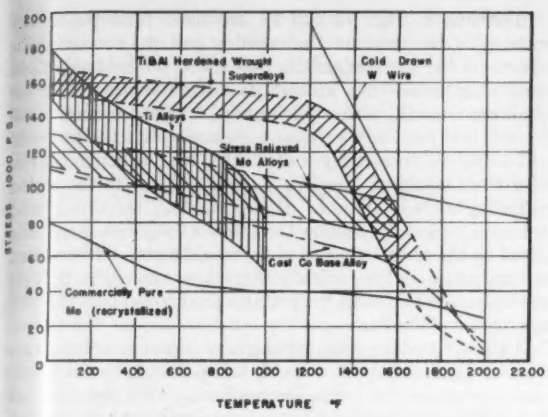

Fig. 7 Short-time hot tensile strength vs. temperature for various alloys

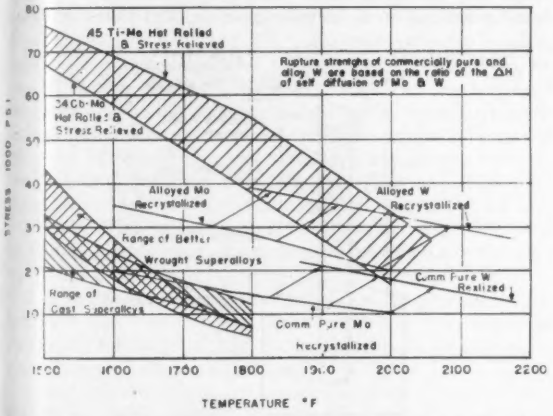
A5 Ti-Mo Hot Rolled & Stress Relieved
Rupture strengths of commercially pure and alloy W are based on the ratio of the ΔH of self diffusion of Mo & W
34 Cb-Mo Hot Rolled & Stress Relieved
Alloyed Mo Recrystallized
Alloyed W Recrystallized
Range of Better Wrought Superalloys
Range of Cast Superalloys
Comm Pure W Recrystallized
Comm Pure Mo Recrystallized
STRESS 1000 P.S.I.
TEMPERATURE °F

Fig. 8 100-hr rupture strength vs. temperature for various alloys

obtained with this metal under certain conditions. It should not be used as a guide of the properties that could be obtained on normal wrought products, if they were available. However, one can speculate that properly alloyed, tungsten base alloys should show strength superior to the molybdenum base alloys plotted, particularly at temperatures in excess of 2000°F.

In Fig. 8, which plots the 100-hr rupture properties versus temperature for a variety of super alloys, the superiority of molybdenum and tungsten is even more striking. The band of properties shown for the wrought super alloys is represented by Inco 700 at the top and Refractaloy 26 at the bottom, both in the solution treated and aged condition. The band for the cast super alloys is based on Stellite 31, which is the best commercial cast alloy in the range of 1700°F to 1800°F.

The 0.34 per cent columbium and 0.45 per cent titanium alloys of molybdenum were "hot cold" rolled at slightly below the recrystallization temperature, 1900°F to 2200°F, then stress relieved at 1800°F. The properties of these stress-relieved alloys (11) approach those of the recrystallized alloys at approximately the recrystallization temperature. The curves for tungsten and tungsten base alloys were not drawn from experimental data, but based on the ratios of the activation energies for creep of pure tungsten to pure molybdenum.

The superior properties of molybdenum and tungsten are presented to demonstrate the need to develop cold hearth melting techniques for them, since it is doubtful they can be melted commercially by any other means. Although cold hearth melting does not, and may never, compete with the more common methods used on tonnage metals, it has been successfully employed in the melting of titanium base alloys, which incidentally is not the primary cause of their high cost. Furthermore, continued experience with the process will probably improve it and lower its cost, and it is not difficult to visualize the cold hearth furnace as a continuous melting method, the ingot being constantly withdrawn and cut into convenient lengths, as the raw material is fed into the top. Parenthetically, it can be said that continuous melting is only in the development stage in steel production. Already the cold hearth furnace is being used to melt some of the present-day iron base high temperature alloys, and it is probable the basic simplicity of the method will mean its extensive use on many other alloys.

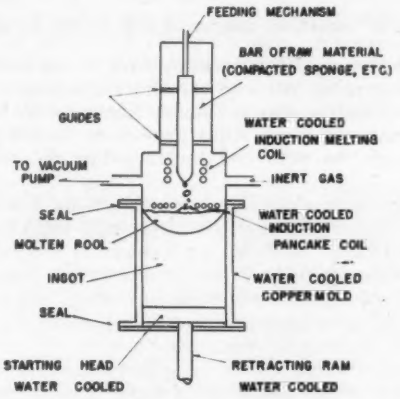

Fig. 9 Schematic diagram of drip pool melting furnace

Another method, which has recently been developed (12) to melt alloys of high melting points and/or high reactivity with refractories, is basically a modification of the cold hearth furnace, and is commonly referred to as "drip pool" melting. Fig. 9 illustrates the equipment, which to date has been operated on a laboratory basis only. In essence the primary difference between this method and cold hearth melting is the fact that the entering raw material, although still in electrode form, is melted by an induction coil through which it passes, rather than by the action of an arc. As the bar melts it drips down into the pool below; however, since the alloy as it drips is barely molten, an additional, pancake induction coil is necessary to superheat the pool slightly in order to promote homogeneity and a sound ingot. The ingot is gradually retracted to keep the molten pool at the proper distance from the pancake coil, while the compacted bar of raw material is fed into the primary cylindrical melting coil as its end melts and drips off.

One of the chief advantages of drip pool melting is that the process may be kept under more complete control. At any time, the melting can be stopped and, by means of a pancake coil, a portion of the ingot kept molten for purposes of refining, making additions, or homogenizing. As with cold hearth arc melting, it is conceivable that the process could be adapted to continuous melting.

Recent modification of the normal cold hearth furnace has resulted in a method whereby reactive metals can be cast to final shape in molds. "Skull melting," as the technique is frequently called, could also be accomplished by similar modification of the drip pool furnace. As commonly practiced (13), skull melting employs the equipment illustrated in Fig. 10. By controlling the pressure during arc melting at slightly above 30 microns, a maximum melting rate is obtained so that a molten pool of approximately 60 per cent of the consumed metal is attained. This molten metal is rapidly poured into the desired mold, usually graphite, leaving a skull in the crucible which represents the remaining 40 per cent of consumed metal. By careful control of melting during successive heats, the skull can be prevented from increasing, thus re-

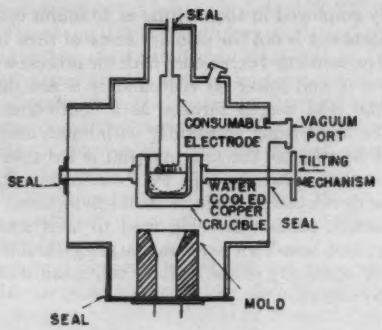

Fig. 10 Schematic diagram of skull melting furnace

sulting in virtually 100 per cent recovery of consumed metal. Although graphite crucibles can be used in place of water-cooled copper, in order to obviate the necessity for rapid melting rates and heavy skulls, there exists the risk of burning through the skull and contaminating the melt with carbon.

Castings of titanium have been successfully made by this method, and it is possible that the technique could be applied to molybdenum. However, molybdenum in cast form tends to be brittle, especially at lower temperatures, if only small amounts of oxygen are present in the casting. Close control of deoxidation during melting must be achieved if this method is to be applied to molybdenum base alloys.

For an increasing number of applications, it is becoming necessary to obtain metals with a degree of purity unrealized in the past. For most commercial uses the impurities other than gases need not be reduced below 0.01 per cent in a metal or a particular alloy. However, in the field of rectifiers and transistors, for example, to obtain satisfactory performance from silicon or germanium, the impurity level must be of the order of parts per million or billion. The process for accomplishing this purity, which has gained considerable importance in the past few years, is called zone refining (14). Referring to Fig. 11, a commercially pure bar of the element to be refined is placed horizontally in a boat or a refractory crucible, contained in a chamber which can be evacuated or purged with an inert atmosphere. The boat is slowly passed through an induction coil, or series of coils, so that successive segments of the bar are melted and resolidified, starting at one end and proceeding to the other. As resolidification takes place, any impurities that lower the melting point of the base metal are rejected to the liquid zone ahead and are thus pushed to the "finish" end of the bar. Conversely, impurities that raise the melting point will tend to segregate toward the "start" end of the bar. Since most impurities lower the melting point, repeated slow passes of the bar through the induction coils usually results in the rejection of virtually all impurities to the finish end of the bar, leaving the starting portion extremely pure.

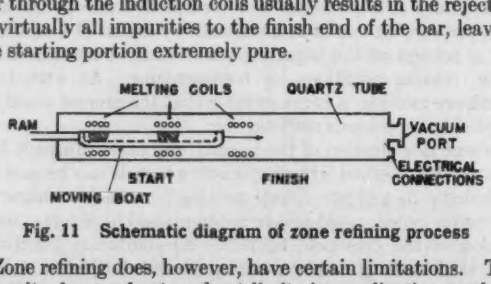

Fig. 11 Schematic diagram of zone refining process

Zone refining does, however, have certain limitations. The necessity for a refractory boat limits its application to those metals which will not react with the refractory. If it is desired to employ zone refining techniques to purify such metals as zirconium, titanium, molybdenum, tungsten, etc., some means must be found to eliminate the refractory boat. This has led to the development of "cage zone refining" (15) which has been applied successfully to zone refine some of the so-called "reactive" metals.

Referring to Figs. 12 and 13, the basic principle of cage melting is to eliminate the crucible and its contaminating effect. A bar of commercially pure metal is machined to produce longitudinal fins around its circumference. This bar standing vertically is slowly lowered through an induction coil to melt and resolidify successive segments, but the power input to the coil is carefully controlled so that although the core of the bar is melted, the fins, being cooler due to the greater radiating surface, are not. Hence the fins, remaining solid, act as a "cage" to confine the molten core within it, being aided by the surface tension of the liquid metal. In addition, the induction coil is conically shaped, as shown, so that the electro-magnetic forces from it also tend to support the molten section of the bar.

Although to date, zone refining and cage zone refining have had importance only in research and particularly the field of semiconductors, the increasing realization that minor impurities in high-temperature alloys play a dominant role in affecting properties may result in the need to purify certain melting raw materials by these techniques. Although such an extreme may seem farfetched today, zone refining is already being practiced on a fairly large scale, and there exists at

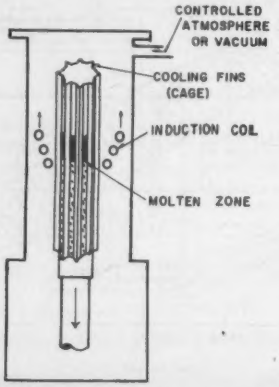

Fig. 12 Schematic diagram of cage zone refining process

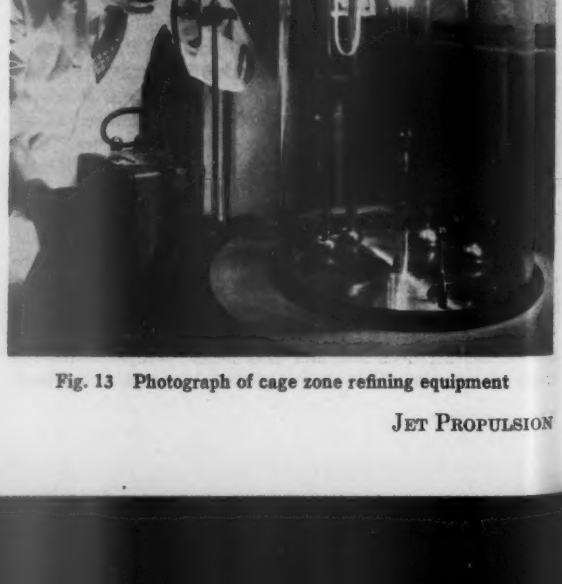

Fig. 13 Photograph of cage zone refining equipment

least one method of making the process continuous and, possibly, not too expensive. Furthermore, one has only to go back a couple of decades and find that the idea of cold hearth melting was considered commercially impractical, to realize how rapidly a technical curiosity can turn into a commercial necessity.

New Fabrication Processes

Although many of the new metallurgical processes seem to lie in the field of melting, this may well be due to the fact that melting is the first problem encountered when investigating many of the new alloys discussed. However, the problems they create in conditioning, forming, fabricating, and heat treatment have begun to attract attention and doubtless will result in new techniques for these steps. Some have already been developed and deserve mention.

Often the next processing step which follows melting and casting is that of conditioning the ingot to remove surface defects, inclusions, and porosity in order to promote good workability. Since most of the new alloys are being cast under vacuum or inert atmospheres, inclusions or dirt do not present a great problem but the ingot surfaces often contain laps, folds, cold shuts, and porosity, which should be removed before forging or rolling. Although conventional methods of grinding or machining are usually employed, the value of the alloy in some cases militates against the loss of material involved. For example, several concerns have recently been using a technique for smoothing zirconium ingot surfaces by Heliarc fusion which entails essentially no loss of material. This operation must be performed in an evacuated chamber or in an inert atmosphere to prevent contamination of the ingot surface during fusion.

The successful fabrication of several of the new high temperature alloys can, in part, be attributed to the fortuitous recent development of such forming processes as extrusion, impacting, and single pass rolling.

Although extrusion of nonferrous alloys of copper and aluminum has been practiced for some time, the practical application of the process to higher melting alloys of iron, nickel, cobalt, molybdenum, etc., had to await the development of a satisfactory high temperature lubricant to prevent prohibitive die wear at the higher temperatures and pressures required. The introduction a few years ago of the Sejournet glass lubricant process (16, 17) has resulted in the successful extrusion of a wide variety of steels, high temperature alloys, and high melting metals such as molybdenum. The extrusion billet, which has usually been preheated in a gas-fired furnace and brought to extrusion temperature in a salt bath or by induction heating, is rolled to the press over a table covered with powdered glass. A fiberglas disk is placed in the die ahead of the billet, and the extrusion ram forces the material through the die to form a variety of simple or highly complex shapes, including tubing or other configurations of hollow centers. Since extrusion pressures range from 50 to 100 tons per square inch, the 1500–2500 ton presses commonly used are limited to starting billets of 6 to 8 inches in diameter and about 24 inches long.

An important aspect of this development is the fact that some of the new alloys being investigated exhibit such poor workability that extrusion is the only way they can be formed, at least during ingot breakdown, if not thereafter. The bulk of the cold hearth melted molybdenum alloys have to date been extruded to at least the billet stage, while the iron-aluminum and nickel-aluminum alloys may well in the future be worked by this process. Extrusion has the advantage over forging or rolling that, since the material is contained in all directions, the tendency during deformation for failures to initiate at grain boundaries is greatly reduced. In addition, since working takes place in a single pass, very heavy reductions can be effected in a matter of a few seconds and with a minimum of oxidation of the piece.

An interesting development in the field of forging is the new technique often referred to as "Impacting" (18, 19). Developed by the Chambersburg Engineering Company, the process consists, in essence, of supporting the work to be forged between two horizontally moving dies (Fig. 14), in contrast to normal practice which involves supporting the work on a stationary die and striking it vertically with the other die. Several technical advantages for the process have been demonstrated in theory and practice. Since the material is struck by two dies instead of one, and since virtually all of the energy is transmitted to the work, instead of losing part of it to the anvil, it has been shown that less energy is required to obtain a given deformation than in conventional forging. Depending on the conditions, up to 100 per cent more work can be accomplished than with a forging hammer delivering a blow of the same number of foot pounds. Since no extensive foundations are required and work handling can be successfully accomplished by conveyor lines, Impacting is admirably suited to automation as a part of an automatically controlled production line.

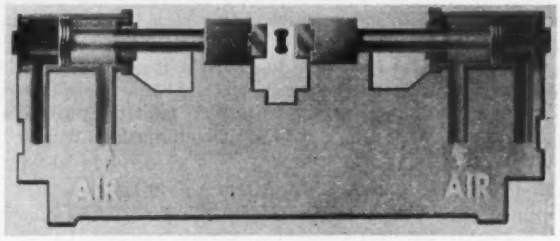

Fig. 14 Schematic diagram of the impacting forging process

The particular significance of Impacting in the field of new high temperature alloys is the degree of control attainable. Since in conventional forging the stationary die cools and restricts the flow of the work, temperature and deformation are nonuniform. In Impacting, die contact time is a very minimum and deformation takes place uniformly about the axis of the work. The process proceeds so quickly that considerable energy is put into the work and far better temperature uniformity during forging is obtained.

It is fortunate also that as new alloy investigation revealed the need for precise control of temperature during hot strip rolling, a unique mill was developed that permitted a degree of temperature control hitherto unattainable. Conventional hot rolling involves the breakdown of a slab and hot strip reduction in a series of passes on several stands. Since normally all these operations must be accomplished in one heat over a period of a minute or more, it is obvious that the temperature of the work falls considerably by the time the final hot strip gage is achieved.

However, as previously mentioned, several of the new alloys being investigated can apparently be hot rolled only in a narrow temperature range. The problem of accomplishing this has been fairly well solved by the Armzen planetary mill (20) which can hot roll a slab to strip on a single stand in one pass. The mill (Fig. 15) consists basically of two driven back-up rolls, surrounded by a cluster of small work rolls held in a spring loaded cage to keep them against the back-up roll. The slabs to be rolled are fed through a furnace by a pusher mechanism, and a set of pinch rolls between the furnace and the main stand force the slabs into the mill. Here the small work rolls, traveling at relatively high speed, in effect take a series of small passes on the slab until it is reduced to final gage at the delivery side of the mill. If the process is properly controlled, it is possible to roll a 2–3 inch thick slab to 100–150 mills thick, the normal hot strip range in one pass with very little change in temperature.

The planetary hot mill may have an important bearing on the future of those new alloys which have to be hot worked at

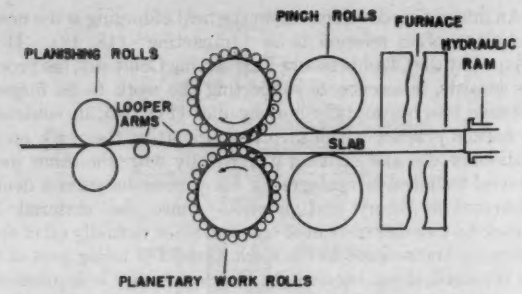

Fig. 15 Schematic diagram of the Armzen planetary hot mill

such a high temperature that grain coarsening is a serious problem. In such cases, rolling in one pass to strip, at which point the material will cool very rapidly, may circumvent this difficulty. Another application for which the mill appears to be well suited is "warm rolling." The Thermenol type alloys have to date been warm rolled in a narrow temperature range around 1000°F, an awkward one for normal rolling equipment. Although on a laboratory basis thin gage warm rolling has been carried out on a four-high mill, using a strip reheating furnace very close to the rolls, it is doubtful that this technique would be practical on a commercial basis. However, the hot planetary mill would probably provide a feasible method of rolling strip in this intermediate temperature range.

Table 2 Elevated temperature-properties of Thermenol compared with some stainless steels

Alloy	Test temperature	Stress, psi	Stress rupture life (sheet values)
Type 403 Stainless 12% Cr	1100° F	25,000	20 hr
Type 316 Stainless 17% Cr, 12% Ni, 2.5% Mo	1200° F	28,000	100 hr
Type 321 Stainless 18% Cr, 8% Ni (Ti stabilized)	1200° F	22,000	100 hr
Thermenol	1100° F	25,000	670 hr
	1200° F	25,000	47.6 hr

The importance of finding satisfactory methods to process alloys of this type can be realized if the combination of low strategic alloy content and good high temperature properties is considered. Although, due to the need to vacuum melt and warm roll, the Thermenol type alloys are hardly competitive with stainless steel, the property comparison shown in Table 2 points out their potential value. Eventual improvement of the alloy and its processing coupled with increasing criticality of nickel may result in the practical application of iron-aluminum alloys of this type.

The last technique to be discussed is really not a process in itself but a way of performing many processes. In view of the care which is presently being taken to prevent contamination of the newer alloys during their melting and heat treating, it would seem eventually necessary to extend this precaution to the hot forming operations. As a result serious thought is being given to sealing off entire rooms so that they can be filled with an inert gas. In this way forging, hot rolling, even extrusion could be performed under the protection of argon or helium, while the operating personnel went about their various jobs donned in space suits, helmets, and oxygen supply systems. There seems to be little doubt that this step will be taken in the near future, in an effort to protect the newly acquired virginity of the reactive metals.

Conclusion

No attempt has been made to give a comprehensive coverage of all new metallurgical processes; rather, those of particular interest and importance in the field of high temperature metallurgy have been briefly discussed. Even in this field attention should be paid to several other developments which may have considerable significance in the future. For example, the powder metallurgy aluminum alloy known as "SAP" (21) may find good application in the moderate temperature range. Certainly, the basic principle involved in "SAP," namely, combining the base metal with its oxide for high temperature strength, will be investigated for its applicability to other alloys for higher temperature service. Vacuum heat treating, which is just beginning to gain commercial stature, will undoubtedly become commonplace in the near future. Since metals have their limitations, it is likely that the metal compounds, carbides, oxides, nitrides, borides, and silicides will find wider application in coming years. Metal coating and cladding for oxidation resistance represents a field in itself, while the need for transpiration cooling will undoubtedly create some interesting fabrication problems.

Finally, there is the problem, mentioned at the outset, of pilot facilities to try out and establish new processes on a practical scale. Historically, the primary metal industries have not provided such pilot plants, because there was insufficient economic incentive to do so, particularly since they had no control over the end products which would result from new alloy development. However, the field of metallurgy is now moving too rapidly to permit continued avoidance of the pilot-plant stage of development, and it is the consumer of specialty alloys who is now supplying these urgently needed facilities. Actually, with the wide variety of entirely new materials now appearing, it is the electrical industry which seems to be investing most heavily in pilot plants, since it is one of the largest users of the so-called "exotic" alloys. However, it is hoped that many other industries will provide facilities to fill this gap between research and production in order to accelerate the difficult process of scaling up a new development to practical application.

Acknowledgment

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Two Methods for Measuring Ignition Delays of Self-Igniting Rocket Propellant Combinations

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Two methods are described for measuring the ignition delays of self-igniting liquid rocket propellant combinations at various conditions of simulated altitude. One consists of a modified open-cup apparatus in which rapid propellant mixing is obtained by crushing a fuel-filled glass ampule under the surface of the oxidant. The delay from propellant mixing to appearance of flame is measured by various electronic means. The other method uses a transparent-sided rocket engine of approximately 50-lb thrust. The delay from propellant impingement to ignition is obtained from high-speed photographic data. Some results obtained by these methods are presented and compared.

Introduction

AN IMPORTANT consideration in the selection of a self-igniting rocket propellant combination is its ignition delay, a parameter usually defined as the time interval from the meeting of the propellants to the point of ignition. Also important is the manner in which this delay is influenced by factors such as temperature, ambient pressure, and oxidant-to-fuel weight ratio.

Ignition delays have been measured satisfactorily by several methods that may be grouped into three basic categories: (a) open-cup, in which one propellant is introduced into the bulk of the second propellant contained in a partially enclosed vessel (1);[2] (b) impinging jet, in which streams of the two propellants meet in space or upon some third body and are not confined by a rocket combustion chamber (1); and (c) rocket engine, in which means are provided for ignition-delay measurement under practical operating conditions.

Two of these methods have been used by the NACA Lewis laboratory in its ignition-delay determinations. One employs a bench-type laboratory setup known as the "modified open-cup apparatus" and the other utilizes a small-scale rocket engine of approximately 50-lb thrust (2). The open-cup unit is used principally for rapid screening of different propellants at temperatures to −105 F. The small-scale engine apparatus also measures delay at various temperatures. In addition, it is useful in the study of the effects on ignition delay of initial ambient pressure, combustion-chamber configuration, and other factors not amenable for investigation with the open-cup apparatus.

Modified Open-Cup Apparatus

Description of Apparatus

As shown in Figs. 1a, b, the modified open-cup apparatus consists, in part, of a test-tube reaction vessel into which a small amount of oxidant is introduced. A sealed glass ampule containing the fuel is immersed in the oxidant. The temperature of the propellants is regulated by a constant-temperature bath surrounding the test tube. The propellants are mixed when a falling weight hits a steel rod which, in turn, crushes the ampule. Simultaneously, time-measuring instruments are actuated. The end of the ignition-delay interval, indicated by the commencement of a continually persistent flame, is automatically recorded by these instruments.

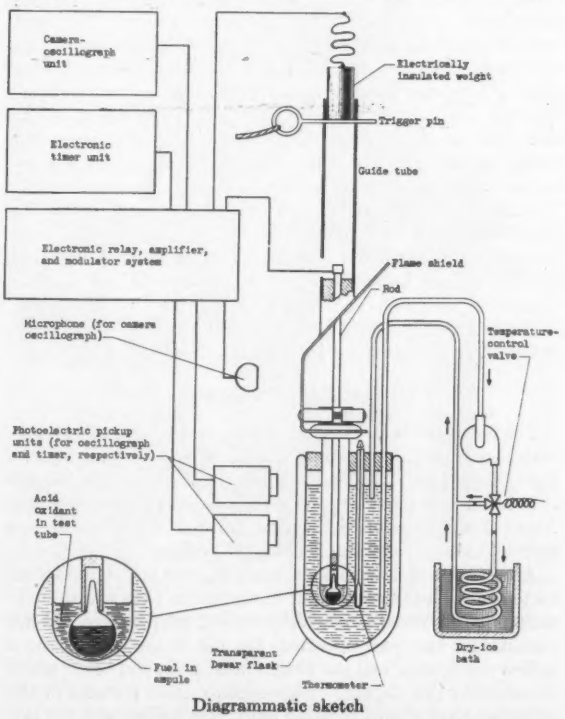
The combustion chamber is a pyrex ignition-type test tube measuring 1 inch in diam and 8 inches in length. The glass fuel ampules are approximately $^{9}/_{16}$ inch in diam. The stainless-steel rod used to crush an ampule is about twice the length of the test tube. A 0.4-lb weight located 6 inches above the top of this rod and contained in a guide tube is used to provide the impact force. During the propellant-loading operation, it is restrained from falling by means of a supporting pin inserted through the guide tube.

Temperature Control

The temperature-control system consists of a clear glass Dewar cylinder ($2^{3}/_{4}$-in. ID), a coolant pump, an alcohol-dry ice heat exchanger, and the required pipes and valves. The temperature is automatically regulated by a solenoid-operated mixing valve and an adjustable temperature-actuated switch. The Dewar cylinder contains a thermometer for indicating coolant temperature.

Instrumentation

Generally, three simultaneous measurements of ignition delay are made in each experiment. They differ with respect



Diagrammatic sketch

Fig. 1a Modified open-cup ignition-delay apparatus

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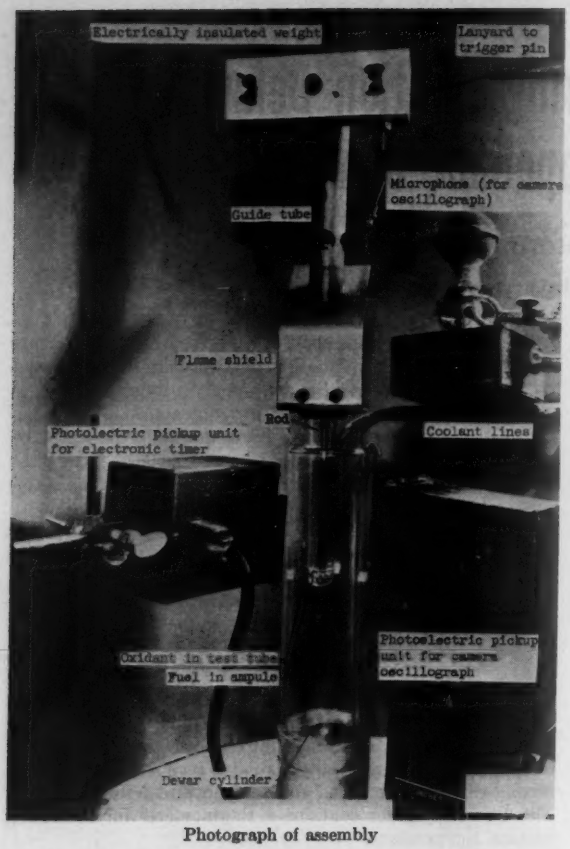
[1] Aeronautical Research Scientist. Mem. ARS.

[2] Numbers in parentheses indicate References at end of paper.



Photograph of assembly

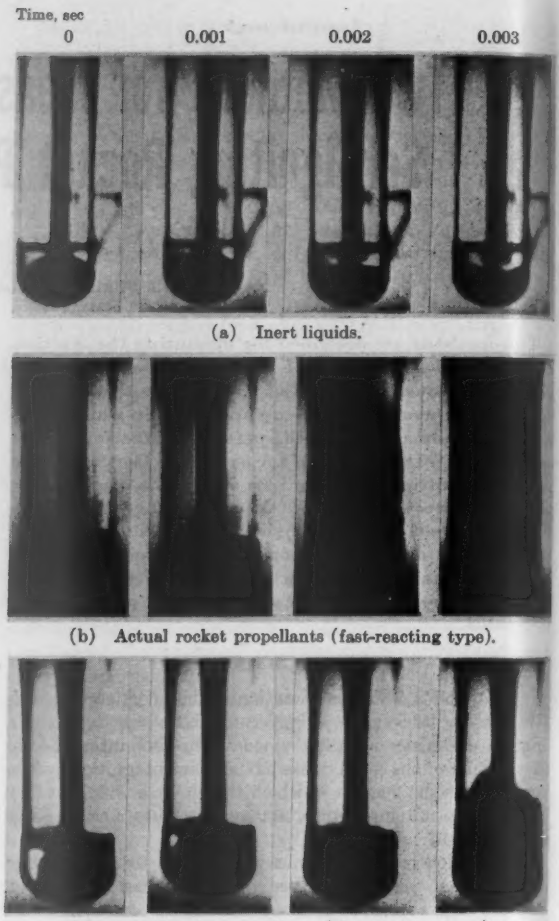
Fig. 1b Modified open-cup ignition-delay apparatus

to the types of signals indicating the starting and ignition points and the means of recording them. In one case, the contact between the falling weight and the rod closes an electric circuit which starts an electronic timer. The light emitted upon ignition strikes a photocell which then stops the timer. In another method, the start of the ignition-delay interval is placed on a camera-type oscillograph by a signal from an argon bulb near the photocell. The signal is the extinction of the bulb by a thyratron at the moment the falling weight hits the rod. The photocell signals are recorded continuously with respect to time by the oscillograph. The signal is a 1000 or 2000 cps carrier wave modulated by the amplified output of the photocell. In the third type of measurement, the amplified output of a microphone placed about one foot from the test tube is recorded on another channel of the same oscillograph used in the second method. In this manner, pressure fluctuations during the reaction are obtained simultaneously with the light-emission record.

Operating Procedure

The fuel ampules are loaded by a hypodermic-needle syringe with about 1 milliliter of propellant in each one. The tips are then flame sealed. As shown in Fig. 1a, the tip of the ampule is inserted into a cavity in one end of the stainless-steel rod. About 3 milliliters of the oxidant are then added to the test tube by means of a remotely operated syringe.

After the loading operation, the test tube is lowered by remote control into the constant-temperature bath and the propellants are allowed to reach the desired temperature. When equilibrium has been obtained, the pin in the guide tube is pulled out quickly and the weight falls on the rod below which then breaks the ampule. High-speed motion pictures of this sequence have shown that the ampule is broken and the propellants are brought into contact in less than 2 millisec. The



(a) Inert liquids.

(b) Actual rocket propellants (fast-reacting type).

(c) Actual rocket propellants (slow-reacting type).

Fig. 2 Positive enlargements from frames of high-speed silhouette motion pictures showing behavior of inert liquids and rocket propellants at room temperature during first 0.003 sec of timed interval. (Ignition occurred sometime after beginning of preliminary nonburning reactions shown)

mixing rate varies slightly between experiments due to differences in the ampules and in the viscosities of various propellant combinations. Some examples of the mixing sequence of liquids with various reactivities are shown in Fig. 2.

Interpretation of Results

Typical examples of oscillograph records are shown in Fig. 3. Elapsed time is indicated by the heavy vertical lines spaced 10 milliseconds apart. In the light-emission records, Fig. 3a, the intensity of the light falling on the photocell is quantitatively indicated by the amplitude of the carrier signal. In the sound records, Fig. 3b, the intensity is indicated by vertical displacement of the output signal.

In experiment 1, Fig. 3a, the start of the ignition-delay period is at A where the argon light is extinguished. At B, a flash of low intensity and short duration occurs. A continuous flame does not start until C which is 37 millisec after A. This period of time represents the ignition delay. In the intervals from D to E and from F to G, the photocell is saturated with strong light. The saturation is identified by a carrier signal of lesser amplitude than the ground signal between A and B.

Experiments 2, 3, and 4 may be interpreted similarly. The irregular fluctuations in the early parts of experiments 2 and 4 are attributed to microphonic pickup rather than flashes, since a flash is identified by a sharp, short disturbance in the signal.

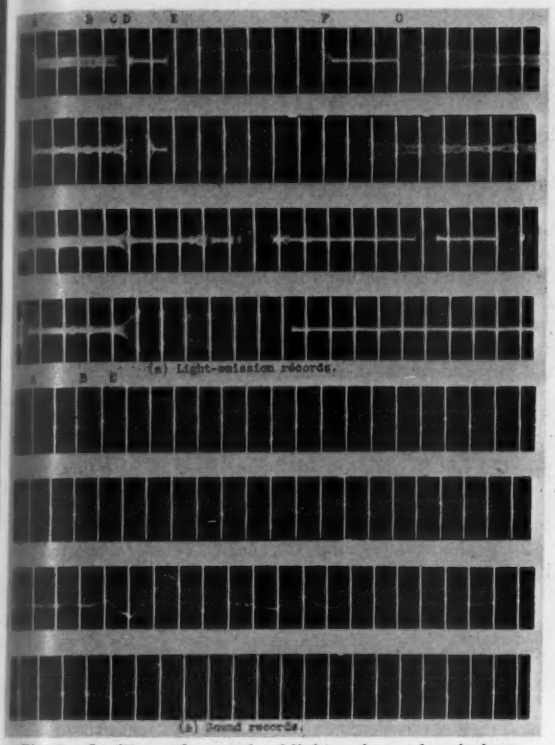


Fig. 3 Oscillograph records of light and sound emissions

The sound records for the same four experiments are shown in Fig. 3b. In experiment 1, the start signal is shown at A where the record becomes fuzzy due to reaction and other noises. This point corresponds to point A on the light-emission record. The dips at B and C also corroborate the light data. Starting at C, the record is difficult to interpret since mechanical vibrations from the apparatus are mixed with the combustion-sound emissions.

The electronic timer often records a shorter delay than the two methods described above because it usually stops counting at the first appearance of light, such as at B, Fig. 3a. It has utility, however, in providing an immediate approximation of the ignition-delay time whereas the other methods do not yield data until the oscillograph film has been processed.

Small-Scale Rocket Engine Apparatus

Description of Apparatus

The small-scale rocket engine apparatus consists of a transparent-sided engine of approximately 50-lb thrust, propellant tanks, a gas-pressure-supply reservoir, means for obtaining and controlling propellant temperature and initial ambient pressure, and instrumentation for indicating and recording combustion-chamber pressure and other operating variables. Fig. 4a is a diagrammatic sketch of the apparatus. A photograph of the over-all equipment is shown in Fig. 4b.

Pressurized helium forces the propellants from their tanks through injector orifices and into the combustion chamber when a quick-opening solenoid valve is actuated. Sealing disks at each end of the propellant tanks are burst in the process. Photographs are taken of the two propellant streams entering the combustion chamber, impinging, diffusing, and then igniting. Measurements of the ignition-delay period, the time interval between the meeting of the jets and the appearance of flame, are made from the photographic data.

The fuel and oxidant tanks have capacities of 100 and 200 cubic centimeters, respectively. Clear plastic tubing, 4 inches long and 2 inches inside diameter, is generally used for the combustion chamber. Reaction products exhaust

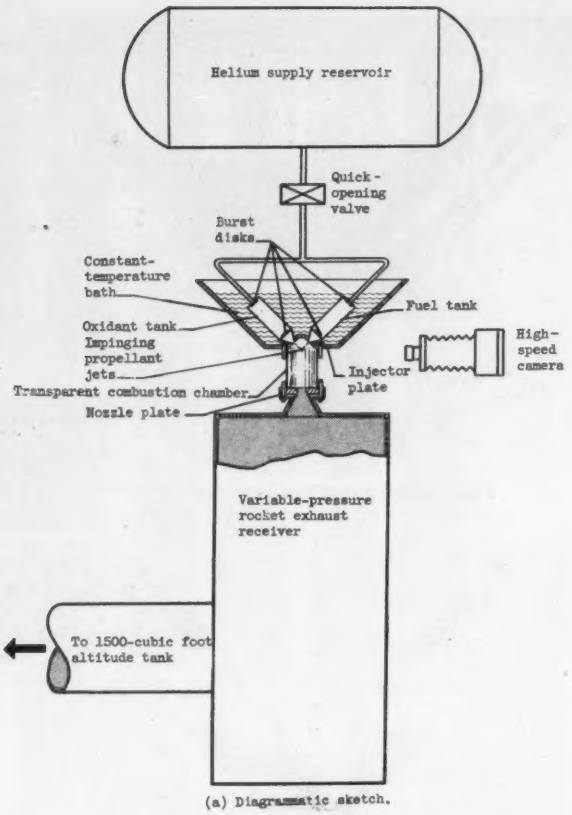


Fig. 4a Small-scale rocket engine ignition-delay apparatus

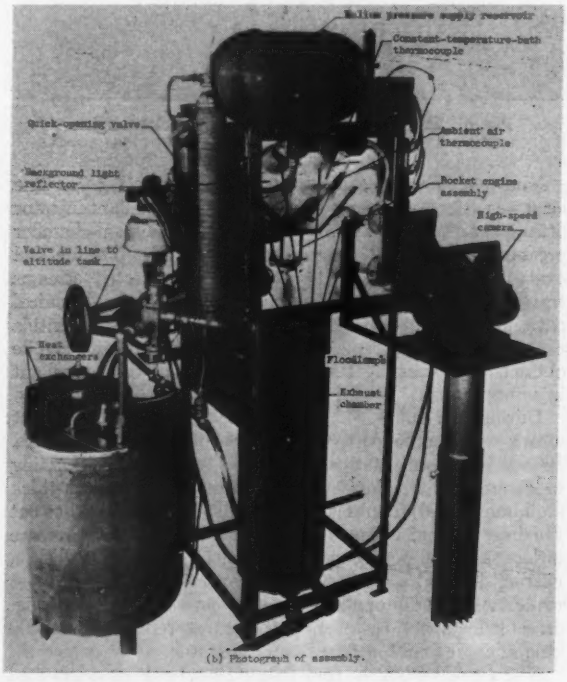


Fig. 4b Small-scale rocket engine ignition-delay apparatus

through a simple convergent nozzle. A photograph of an early model of this rocket-engine assembly is shown in Fig. 5. Fig. 6 shows an exploded view of the same assembly. Later models differ only in minor details.

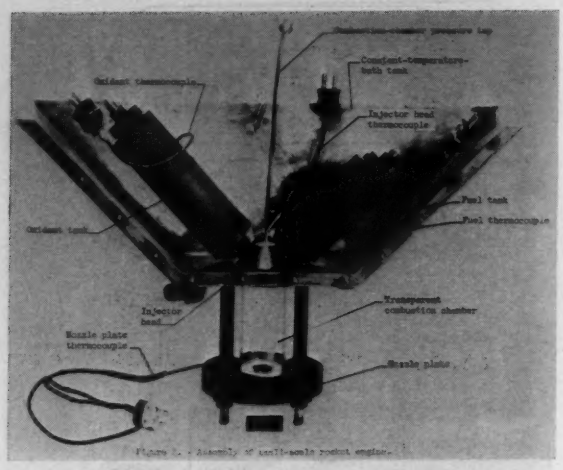


Fig. 5 Assembly of small-scale rocket engine

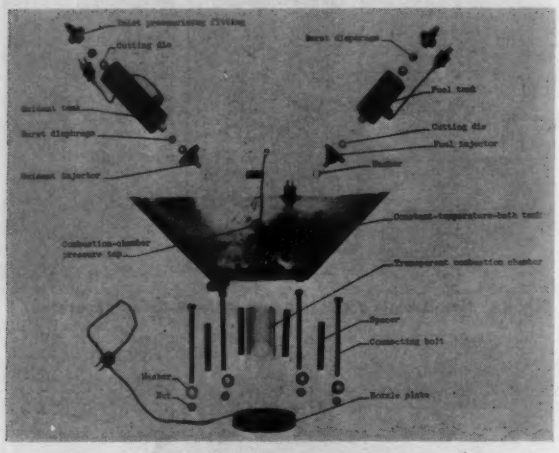


Fig. 6 Exploded view of small-scale rocket engine

A bottom view of the injector head is shown in Fig. 7. The head was drilled and tapped to receive two propellant injector fittings at an included angle of 90 deg. A combustion-chamber pressure tap is located in the center of the head. The fuel and oxidant injectors are located so that the ejected streams travel 0.68 inch before impinging. Each injector has a conical entrance leading to a straight 0.38-inch-long orifice tube with a chamfered exit. Various oxidant-to-fuel weight ratios can be obtained by changing the hole diameters of the propellant injectors.

During the course of experimentation, several different means were employed to rupture the propellant-tank disks. In one successful method, hardened stainless-steel cutting dies were used in conjunction with unscored 0.003-inch-thick aluminum (2S-0) diaphragms. The dies were designed to cut the disks without fragmentation and with an applied pressure of less than 100 pounds per square inch. An unused disk, a cutting die, and a burst disk are shown in Fig. 8. In most experiments, the propellant-injection pressure was 450 psig. In some instances, however, the pressures were as high as 600 psig, the safe limit for the existing apparatus.

The action within the combustion chamber is photographed in silhouette by a 16-millimeter camera with a built-in argon timing light and with a maximum speed of about 6000 frames per sec. The required light is produced by a bank of flood lamps focused on a white background with the reflected light passing through the combustion chamber and into the camera lens. The photographic installation can be seen in Fig. 4b.

Pressure and Temperature Control

The rocket engine is mounted vertically on a large standpipe connected to a 1500-cubic-foot cylindrical tank that can be evacuated to an NACA standard pressure altitude of about 100,000 feet.

The propellant tanks are immersed in a constant-temperature alcohol bath contained in a tank that is either bolted or welded directly to the injector head, Figs. 5, 6. The temperature of the bath is accurately and automatically controlled by means of a dual heat-exchanger and blending system. Any desired propellant temperature in the range from −100 F to 160 F can be obtained within 20 minutes after starting the circulation pump in the system. A mixture of dry ice and denatured alcohol, and electrically heated water are used in the cold and hot heat exchangers, respectively.

Instrumentation

The only direct measurements that are made are those of pressure and temperature and, generally, are as follows:

1 Combustion-chamber, propellant-injection, and altitude-tank pressures.

2 Fuel, oxidant, injector head, constant-temperature bath, nozzle plate, and ambient air temperatures.

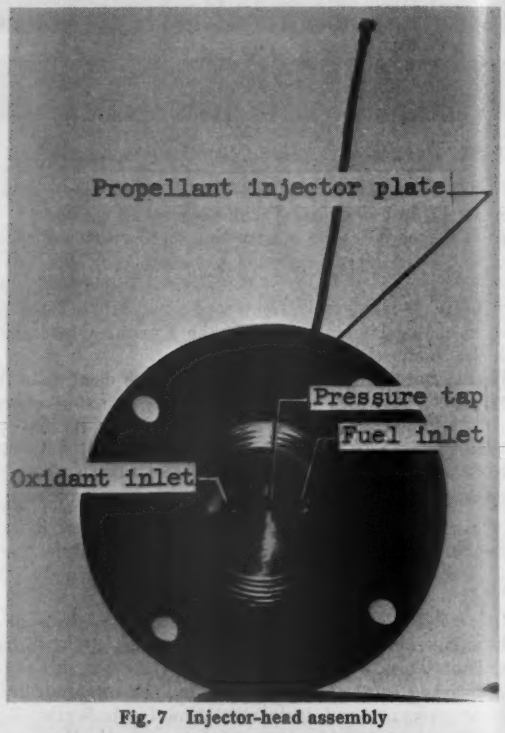


Fig. 7 Injector-head assembly

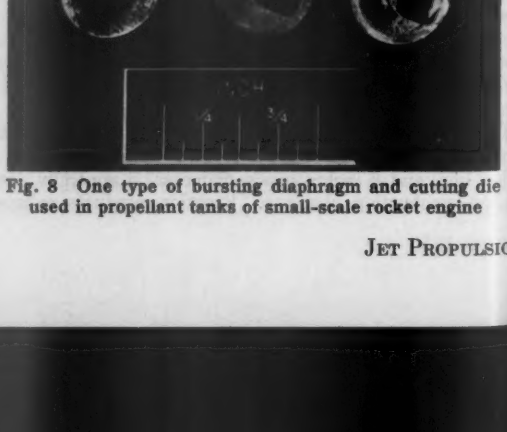


Fig. 8 One type of bursting diaphragm and cutting die used in propellant tanks of small-scale rocket engine

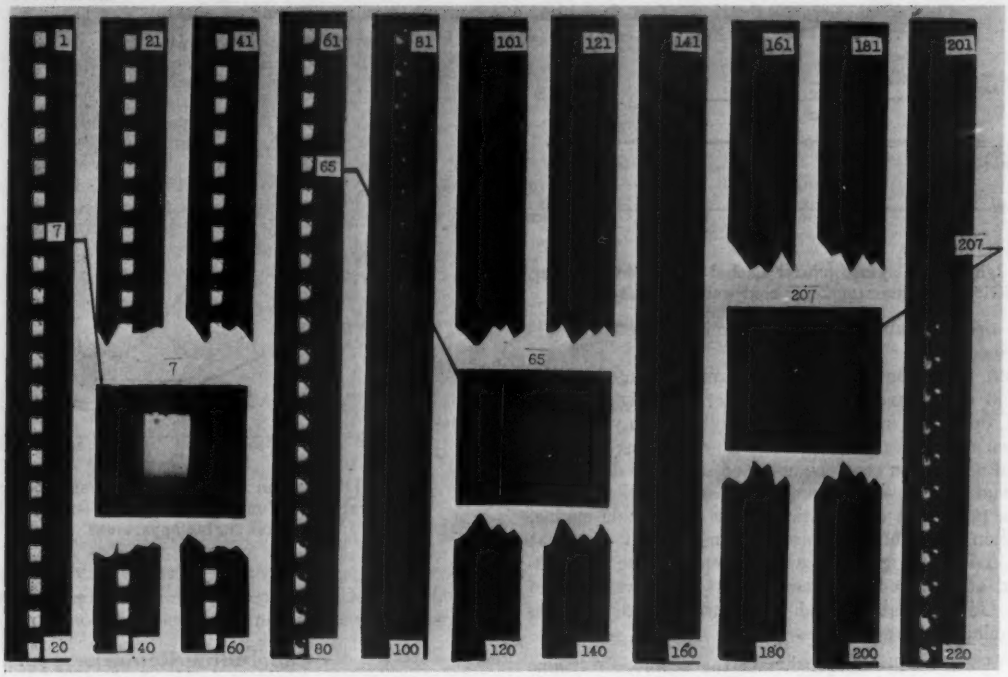


Fig. 9 High-speed photographs of typical run in small-scale rocket engine ignition-delay apparatus

Indirect measurements are obtained from high-speed photographs. In addition to the ignition-delay period, the time between the entries of the two jets into the combustion chamber and the time between ignition and explosion (if it occurs) are also calculated.

Operating Procedure

After loading, the propellant tanks are completely sealed by inserting bursting diaphragms and cutting dies between the tank bodies and end fittings. Equal ullages help in injecting the propellants into the combustion chamber simultaneously.

In one method of assembly, the rocket-engine components are bolted together to a measured torque of about 400 lb-inches. Spacers around the bolts prevent heat distortion of the chamber during a run and consequent leaking. The propellant tanks are then screwed into the injector head and the helium inlet lines are connected to the tanks.

Several methods have been used to supply the desired propellant injection pressure. At the present time, a pressure loader keeps the helium pressure constant before and during a run.

For runs made at pressures different from sea level, the large altitude tank is evacuated prior to firing by a rotating-oil-seal-type vacuum pump which reduces the pressure correspondingly in the exhaust standpipe as well as in the rocket combustion chamber. The pressure in the standpipe does not change significantly during the ignition-delay period.

After the preliminary steps have been completed, the actual operation of the apparatus is almost completely automatic. The entire sequence of events during a normal run is controlled by a preset electrical program timer.

Interpretation of Results

Most runs are photographically similar. In all cases, the exact frame of the entry of each jet into the combustion chamber is clearly discernible. At the moment that the two jets meet, a copious amount of dark fumes begin to be evolved. These fumes quickly fill the chamber and usually make it completely opaque. The ignition point is determined by the frame in which light first appears. It usually encompasses about $^1/_{20}$ to $^1/_4$ of the projected chamber area. In most runs, the bright area increases rapidly and a normal combustion pattern is established in 3 to 6 frames, or about 1 millisec. With some propellant combinations, the ignition point is difficult to determine because the initially lighted area is small and faint and, in some cases, the full combustion picture is not obtained for more than 40 millisec.

The photographic record of a typical run is shown in Fig. 9. Action starts when the oxidant jet enters the combustion chamber (frame 7); 13.7 millisec later, the fuel jet enters and intersects the oxidant stream (frame 65). Fumes are evolved and fill the combustion chamber. Ignition occurs in frame 207, 33.5 millisec after the meeting of the propellants. This is the ignition-delay period. The pressure rise accompanying ignition purges the combustion chamber of dark fumes in 1 millisec and normal burning is established. Photographs made in color have shown that the light recorded at the ignition point is white and, therefore, is actually light emitted by the combustion reaction. If, instead of true ignition, a sudden nonluminous pressure rise had cleared the fumes from the chamber, the transmitted floodlight would have been yellowish.

Examples of Results

Ignition-delay determinations of furfuryl alcohol and mixed butyl mercaptans with various white fuming nitric acids were made at several temperatures with the modified open-cup and small-scale rocket engine apparatus (Reference 2). Complete results of these experiments are shown in Tables 1–4.

A summary of those results which show a comparison between the two apparatus is as follows:

1 With furfuryl alcohol and a white fuming nitric acid containing about 2 per cent water by weight, the average ignition delay in the modified open-cup apparatus was constant and equal to about 25 milliseconds from 22 deg to 2 deg C, Fig. 10. With the same fuel and a similar acid, the average ignition delay in the small-scale rocket engine was also constant and equal to about 16 milliseconds from 50 deg to −20 deg C, Fig. 10.

2 With furfuryl alcohol and white fuming nitric acids containing less than 1 per cent water by weight, the ignition delays at −40 deg C were about 49 millisec (average) in the

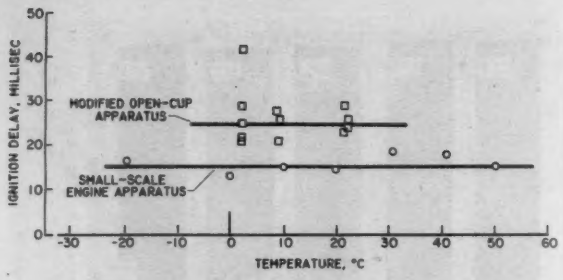


Fig. 10 Ignition delay of furfuryl alcohol and a white fuming nitric acid containing 2 per cent water by weight

modified open-cup apparatus and 54 millisec in the small-scale engine.

3 With mixed butyl mercaptans and a white fuming nitric acid containing 2 per cent water by weight in the modified open-cup apparatus, the ignition delays (about 55 millisec at 21.5 deg C) increased with decreasing temperature until no ignition could be obtained at −38.5 deg C. A nondestructive explosion accompanied each ignition. With the same propellant combination in the small-scale engine, the ignition delay of all measured runs (except two that resulted in doubtful ignitions) at room temperature and pressure, and at various fuel-oxidant weight ratios was 38 ± 4 millisec. All runs at reduced temperatures and pressures were terminated by explosions.

Some of the results obtained with the small-scale engine also show the effect on ignition delay of varying the water content of the oxidant. As shown in Fig. 11, the delays in the furfuryl alcohol-white fuming nitric acid series increase with an increase in the percentage of water.

As a result of the experience gained with the two ignition-delay apparatus over a period of several years, it has been observed that the results are generally similar for the same propellant combinations at the same operating conditions as long as the propellant viscosities are less than about 20 centistokes. As the viscosity increases above this value, ignition delays in the modified open-cup apparatus increase rapidly, but no significant changes in small-scale engine results are observed until the viscosity reaches about 200 centistokes.

An explanation for the effect of viscosity on the ignition delay in the two apparatus probably is that the total mixing is not as rapid nor as efficient in the open-cup as in the small-scale engine. With propellants of low viscosity, the differences in mixing rapidity and efficiency should be slight. With propellants of high viscosity, the differences in mixing, and consequently in ignition delay, should become appreciable.

Table 1 Summary of data obtained with modified open-cup apparatus

(Furfuryl alcohol and white fuming nitric acids)

Propellant temperature, °C	Ignition delay, millisec
Acid with 2 per cent water by weight	
22	26
22	24
21.5	29
21.5	23
9	26
9	21
8.5	28
2	42
2	29
2	25
2	22
2	21
Acid with <1 per cent water by weight	
−40	48.5[1]

[1] Average of 14 runs ranging from 30 to 72 millisec.

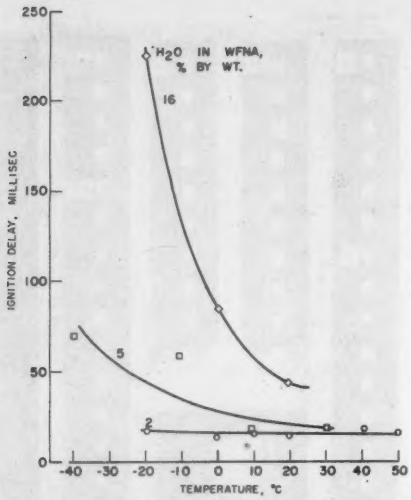


Fig. 11 Ignition delay of furfuryl alcohol and several white fuming nitric acids (small-scale rocket engine apparatus)

Concluding Remarks

The modified open-cup apparatus is suitable and convenient for rapid screening of propellant combinations and for determining the effect of low temperatures on ignition delay, provided the viscosity is not greater than about 20 centistokes. The small-scale engine apparatus is less convenient to use but is more versatile in that the effect on ignition delay of initial ambient pressure, combustion-chamber geometry, propellant flow rates, and oxidant-to-fuel ratios can also be determined. In addition, the apparatus is less sensitive to changes in viscosity of the propellants.

References

1 Broatch, J. D., "An Apparatus for the Measurement of Ignition Delays of Self-Igniting Fuels," *Fuel*, vol. 29, London, 1950.

2 Ladanyi, D. J., Miller, R. O., and Hennings, G., "Ignition-Delay Determinations of Furfuryl Alcohol and Mixed Butyl Mercaptans With Various White Fuming Nitric Acids Using Modified Open-Cup and Small-Scale Rocket-Engine Apparatus," *NACA Research Memorandum* no. E53E29, Cleveland, Ohio, 1955.

Table 3 Summary of data obtained with modified open-cup apparatus

(Mixed butyl mercaptans and white fuming nitric acid containing 2 per cent water by weight)

Propellant temperature, °C	Fuel quantity, ml	Oxidant quantity, ml	Fuel-oxidant weight ratio	Ignition delay, millisec
21.5	1.4	2.6	0.30	52[1]
21.5	1.4	2.6	0.30	57[1]
3.0	1.4	2.6	0.30	63[1]
3.0	1.4	2.6	0.30	70[1]
2.1	1.4	2.6	0.30	85[1]
−18.5	1.4	2.6	0.30	110[1]
−18.5	1.4	2.6	0.30	no ignition
−18.5	1.4	2.6	0.30	no ignition
−38.5	1.4	2.6	0.30	no ignition
−38.5	1.4	2.6	0.30	no ignition
−38.5	1.4	2.6	0.30	no ignition
−38.5	1.4	2.6	0.30	no ignition

[1] Nondestructive explosion accompanied ignition.

Table 2 Summary of data obtained with small-scale rocket engine apparatus

(Furfuryl alcohol and several white fuming nitric acids)

Average propellant temperature, °C	Maximum combustion chamber pressure, lb/sq in. gage	Time to attain maximum combustion chamber pressure, sec	Temperature, °C: Oxidant	Fuel	Injector head	Constant temperature bath	Nozzle plate	Ambient air	Lead propellant into combustion chamber	Time between jet entries into combustion chamber, millisec	Ignition delay, millisec
Acid with <1 per cent water by weight											
−40.0	170[1]	3.4[2]	..	−40	−36.1	−40.6	12.2	17.2	oxidant	63.3	53.7
Acid with 2 per cent water by weight											
50.0	285	0.6	50.0	50.0	51.7	51.1	30.6	30.0	fuel	0.2	15.6
40.6	290	0.7	40.6	40.6	41.1	41.1	23.9	25.6	oxidant	0.6	18.1
30.3	280	0.6	30.0	30.6	30.0	30.0	20.6	18.3	oxidant	24.2	18.9
19.7	230	0.6	20.0	19.4	20.0	19.4	25.6	27.8	fuel	8.1	14.8
10.0	297	0.6	10.0	10.0	10.6	10.6	23.3	19.4	fuel	14.9	15.4
−0.3	280	0.6	0.0	−0.6	0.6	0.0	20.6	25.0	oxidant	5.0	13.1
−19.7	270	0.6	−20.0	−19.4	−19.4	−19.4	16.1	28.7	oxidant	20.2	16.9
Acid with 5 per cent water by weight											
30.0	200	0.4	30.0	30.0	30.0	29.4	20.0	17.8	oxidant	2.7	18.1
9.4	190	0.5	9.4	..	9.4	9.4	17.2	22.2	fuel	18.4	18.1
−10.6	[3]	[3]	−10.6	..	−10.0	−10.6	11.7	13.9	oxidant	25.8	58.8
−40.0	80	0.6	−40.0	..	−39.4	−41.1	13.9	12.8	oxidant	40.5	69.9
Acid with 16 per cent water by weight											
19.4	187	0.4	19.4	19.4	20.0	20.0	24.4	25.6	fuel	8.6	42.7
0.0	150	0.5	0.0	0.0	0.6	0.6	22.2	21.7	oxidant	9.4	84.8
−20.3	113	0.3	−20.0	−20.6	−18.3	−18.9	17.8	20.0	fuel	11.4	225

[1] Peak pressure; maximum pressure possible was probably not attained.
[2] Time to attain peak combustion-chamber pressure.
[3] No chamber-pressure record.

Table 4 Summary of data obtained with small-scale rocket engine apparatus

(Mixed butyl mercaptans and white fuming nitric acid containing 2 per cent water by weight)

Average propellant temperature, °C	Initial ambient pressure, mm Hg	Maximum combustion chamber pressure, lb/sq in. gage	Time to attain maximum combustion chamber pressure, sec	Temperature, °C: Oxidant	Fuel	Injector head	Constant temperature bath	Nozzle plate	Ambient air	Lead propellant into combustion chamber	Time between jet entries into combustion chamber, millisec	Time between ignition and explosion, millisec	Fuel-oxidant weight ratio	Ignition delay, millisec
22.2	≈760	280	1.3	22.2	22.2	22.2	22.2	20.6	22.2	oxidant	0.6		0.30	35.0
22.2	≈760	315	1.2	22.2	22.2	22.2	22.8	20.6	22.8	fuel	13.2		0.30	41.4
−37.8	≈760	[2]	[2]	−37.8	..	−36.7	−37.8	11.7	17.2	fuel	0.3	0.7	0.30	406
−37.8[1]	≈760	[2]	[2]	−37.8	−37.8	−37.2	−37.8	13.3	18.3	fuel	0.8	[3]	0.30	>575[4]
21.7	48.8	[2]	[2]	21.7	21.7	21.7	22.2	18.9	21.7	fuel	3.4	0.8	0.30	72.5
22.2	50.0	[2]	[2]	22.2	22.2	22.2	22.2	18.9	20.0	[5]	[5]	[5]	0.30	[5]
22.2	49.5	[2]	[2]	22.2	22.2	21.7	22.2	19.4	19.4	fuel	7.4	<.2	0.30	95.3
22.5	≈760	315	1.5	22.2	22.8	22.8	22.8	21.1	22.2	oxidant	0.6		0.40	37.5
22.2	≈760	310	1.5	22.2	22.2	22.2	22.2	21.1	23.3	oxidant	1.6		0.40	38.8
22.2	≈760	[6]	[6]	22.2	22.2	22.2	22.2	20.0	21.1	fuel	3.6		0.20	>536[4,7]
22.2	≈760	[6]	[6]	22.2	22.2	22.2	22.2	21.1	22.2	fuel	0.3		0.20	>510[4,7]
22.0[8]	≈760	180	1.6	22.2	21.7	22.8	..	22.2	23.3	[9]	[9]		0.20	[9,10]
22.2	≈760	180	1.0	22.2	22.2	22.2	22.2	21.1	22.2	oxidant	0.6		0.20	34.4

[1] Heavy cylindrical steel shield slipped over plastic combustion chamber to contain explosion.
[2] Explosion.
[3] Explosion occurred after end of film roll.
[4] Ignition occurred after end of film roll.
[5] No photographic records because of defective electric system.
[6] Restriction in line from combustion chamber to pressure recorder.
[7] Doubtful ignition.
[8] Run made in complete darkness for visual check of doubtful ignitions of two preceding runs.
[9] No film records made.
[10] Positive ignition, observed audibly and visually.

Solution of Thermochemical Propellant Calculations on a High-Speed Digital Computer[1]

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The problem of carrying out performance calculations on rocket fuels has been solved on a high-speed digital computer. Mathematically, the problem resolves to the simultaneous solution of a group of nonlinear algebraic equations which yield gas composition, flame temperature, average molecular weight, exhaust velocities, and other performance parameters. A three-cycle iterative scheme has been developed for the simultaneous solution for the various components involved in chemical combustion phenomena. Following the iteration, a straightforward computation obtains the performance parameters. With the present floating-decimal programming, the digital computer provides a complete solution for propellant performance calculations in an average time interval of approximately thirty minutes. The computing time previously required for the solution of these problems by desk calculation was measured in terms of days.

Nomenclature

c	= exhaust velocity
c_F	= thrust coefficient
c_p	= isobaric heat capacity
c_v	= isochoric heat capacity
c^*	= characteristic velocity
C	= moles of carbon atom in system
g	= constant of gravity = 32.174.
H	= moles of hydrogen atom in system
$\Delta H_T{}^{T_c}$	= enthalpy difference between chamber and exhaust
$(\Delta H_{298}{}^T)_i$	= enthalpy of the i^{th} component of the product gases
I_{sp}	= specific impulse
K_i	= equilibrium constant
m	= mass of the propellant in grams
M	= molecular weight of the product gases
N	= moles of nitrogen atom in system
n_i	= moles of the i^{th} component of the product gases
n_j	= moles of the j^{th} component of the reactant gases
O	= moles of oxygen atom in system
p_i	= partial pressure of the i^{th} component of the product gases (cf. Eqs. [2-7])
P	= pressure
$(Q_f)_i$	= heat of formation of the i^{th} component of the product gases
$(Q_f)_j$	= heat of formation of the j^{th} component of the reactant gases
R	= gas constant
$S_i{}^T$	= entropy of the i^{th} component of the product gases
$\Delta S_{T_e}{}^{T_c}$	= entropy difference between chamber and exhaust
T	= temperature
γ	= ratio of the specific heats of the gases during expansion
$\Gamma(\gamma)$	= function of γ (cf. Eq. [41]).
σ	= total moles of product gases

Throughout the paper, the subscripts c and e refer to the chamber and exit conditions, respectively, and $(\overline{\ }) = \frac{1}{2}[(\ )_c + (\ )_e]$ = average property during expansion.

Presented at the ARS Fall Meeting, Los Angeles, Calif., Sept. 18–21, 1955.

[1] This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. DA-04-495-Ord 18, sponsored by the Department of the Army, Ordnance Corps.

[2] Junior research engineer.

[3] Senior research engineer.

I Introduction

UNTIL very recently, thermochemical propellant calculations were performed by means of desk calculators, a process which required a day or more for each solution. The calculations, which involve the simultaneous solution of several nonlinear algebraic equations, are well suited to solution by a high-speed digital computer. Accordingly, these proglems were among the first to be programmed and coded for the ElectroData[4] (model 30-202) computer at the Jet Propulsion Laboratory.

A code has been developed and put into service that performs thermochemical calculations and propellant performance parameter calculations in an average time interval of approximately thirty minutes. The code operates on the basis of a three-cycle iterative scheme for the determination of the chamber conditions or the combustion gas composition, followed by a straightforward calculation of the performance parameters. This paper describes the thermochemical, mathematical, and coding aspects of the problem.

II Thermodynamics and Chemistry Involved

The effectiveness of a chemical propellant as a suitable rocket fuel is determined from the amount of energy available in the combustion of the chemical compounds which make up the propellant. The compounds yielding the largest amount of energy for a given weight of propellant are the most suitable for rocket propellants.

The parameters which indicate the relative effectiveness of a propellant are the exhaust velocity c, which is a direct measure of the chemical energy released during combustion of the propellant in the chamber and the expansion of gases through the nozzle, and the characteristic velocity c^*, which is a direct measure of the combustion efficiency of the propellant.

The theoretical performance is based upon an adiabatic isentropic expansion of the combustion gases from the rocket chamber through the nozzle. With the adiabatic combustion of a propellant in a rocket chamber, an equilibrium flame temperature (called the chamber temperature, T_c) is attained which is characteristic of the products formed during the burning of the propellant.

The theoretical isobaric chamber temperature is defined as the temperature at which the heat of combustion of the propellant is equal to the enthalpy of the gaseous products, relative to the base temperature, or the temperature at which

$$\sum_i n_i(\Delta H_{298}{}^{T_c})_i - \sum_i n_i(Q_f)_i + \sum_j n_j(Q_f)_j = 0 \ldots\ldots [1]$$

The composition of the gaseous products is obtained by the simultaneous solution of the equations involving the various products. As an example, systems containing carbon, hydro-

[4] ElectroData Corp., Pasadena, Calif.

gen, nitrogen, and oxygen require the solution of the following eleven simultaneous equations (1).[5]

Chemical equilibria involved

$$\left.\begin{aligned} K_1 &= \frac{n_{H_2O} n_{CO}}{n_{H_2} n_{CO_2}} \\ K_1 &= \frac{p_{H_2O} p_{CO}}{p_{H_2} p_{CO_2}} \end{aligned}\right\} \quad \ldots\ldots [2]$$

where

$$\left.\begin{aligned} K_2 \left(\frac{\sigma}{P_e}\right)^{\frac{1}{2}} &= \frac{n_{NO} n_{H_2}}{n_{N_2}^{\frac{1}{2}} n_{H_2O}} \\ K_2 &= \frac{p_{NO} p_{H_2}}{p_{N_2}^{\frac{1}{2}} p_{H_2O}} \end{aligned}\right\} \quad \ldots\ldots [3]$$

where

$$\left.\begin{aligned} K_6 \left(\frac{\sigma}{P_e}\right) &= \frac{n_{H_2}^2 n_{O_2}}{n_{H_2O}^2} \\ K_6 &= \frac{p_{H_2}^2 p_{O_2}}{p_{H_2O}^2} \end{aligned}\right\} \quad \ldots\ldots [4]$$

where

$$\left.\begin{aligned} K_7 \left(\frac{\sigma}{P_e}\right) &= \frac{n_{H_2} n_O}{n_{H_2O}} \\ K_7 &= \frac{p_{H_2} p_O}{p_{H_2O}} \end{aligned}\right\} \quad \ldots\ldots [5]$$

where

$$\left.\begin{aligned} K_9 \left(\frac{\sigma}{P_e}\right)^{\frac{1}{2}} &= \frac{n_H}{n_{H_2}^{\frac{1}{2}}} \\ K_9 &= \frac{p_H}{p_{H_2}^{\frac{1}{2}}} \end{aligned}\right\} \quad \ldots\ldots [6]$$

where

$$\left.\begin{aligned} K_{10} \left(\frac{\sigma}{P_e}\right)^{\frac{1}{2}} &= \frac{n_{H_2}^{\frac{1}{2}} n_{OH}}{n_{H_2O}} \\ K_{10} &= \frac{p_{H_2}^{\frac{1}{2}} p_{OH}}{p_{H_2O}} \end{aligned}\right\} \quad \ldots\ldots [7]$$

Mass balances involved

$$H = 2n_{H_2} + 2n_{H_2O} + n_{OH} + n_H \quad \ldots\ldots [8]$$

$$O = n_{H_2O} + n_{CO} + 2n_{CO_2} + 2n_{O_2} + n_{NO} + n_{OH} + n_O \quad \ldots\ldots [9]$$

$$C = n_{CO} + n_{CO_2} \quad \ldots\ldots [10]$$

$$N = 2n_{N_2} + n_{NO} \quad \ldots\ldots [11]$$

$$\sigma = n_{H_2O} + n_{H_2} + n_{CO} + n_{CO_2} + n_{O_2} + n_{N_2} + n_{OH} + n_{NO} + n_H + n_O \quad \ldots\ldots [12]$$

Propellants containing other elements require the solution of additional equations.

The chamber temperature is the temperature at which the composition of the products obtained from the solution of Equations [2] through [12] satisfies Equation [1].

For an adiabatic isentropic expansion, the change in entropy must be equal to zero. This can be written

$$\Delta S_{T_e}^{T_c} = 0 \quad \ldots\ldots [1']$$

where

$$\Delta S_{T_e}^{T_c} = \left[\sum_i n_i S_i^T - \sigma R \sum_i \frac{n_i}{\sigma} \ln \frac{n_i}{\sigma} - \sigma R \ln P\right]_c - \left[\sum_i n_i S_i^T - \sigma R \sum_i \frac{n_i}{\sigma} \ln \frac{n_i}{\sigma}\right]_e$$

When it is desired to allow for expansion to subatmospheric conditions, the term $(\sigma R \ln P)_e$ must be added to the right-hand side of the above equation. In the code currently in use, this term has been omitted.

The exit temperature is the temperature at which the composition of the products obtained from the solution of Equations [2] through [12] satisfies Equation [1'].

The total enthalpy change during the expansion, including both sensible and chemical energy, is given as

$$\Delta H_{T_e}^{T_c} = \left[\sum_i n_i (\Delta H_{300}^T)_i - \sum_i n_i (Q_f)_i\right]_c - \left[\sum_i n_i (\Delta H_{300}^T)_i - \sum_i n_i (Q_f)_i\right]_e \quad \ldots\ldots [13]$$

For frozen flow, the n_i's are constant and the chemical contribution to the enthalpy change is, therefore, zero. The exhaust velocity c is related to the energy released as

$$c = \sqrt{\frac{2\Delta H_{T_e}^{T_c}}{m}} \quad \ldots\ldots [14]$$

The specific impulse I_{sp} is the exhaust velocity divided by the constant of gravity.

$$I_{sp} = c/g \quad \ldots\ldots [15]$$

The characteristic velocity c^* is obtained from the following approximate relationship

$$c^* = \frac{299.5\sqrt{T_c/M}}{\bar{\gamma}^{\frac{1}{2}} \cdot \left(\frac{2}{\bar{\gamma}+1}\right)^{\frac{\bar{\gamma}+1}{2(\bar{\gamma}-1)}}} \quad \ldots\ldots [16]$$

III Mathematical Statement of the Problem

In this section, the problem of performance calculations for systems involving only C, H, O, and N will be discussed from a general computational point of view without regard to the equipment to be used.

A Translation from Chemical Notation

In order to facilitate the expression of the essential mathematical structure of the problem, it is convenient to replace the chemical notation with an entirely new system of symbols and to define some additional terms. (See Table 1.)

Table 1 Translation from chemical notation to mathematical notation

Variables		Constants		Parameters	
n_{H_2}	$\rightarrow x_1$	H	$\rightarrow a_1$	K_1	$\rightarrow K_1(T)$
n_{H_2O}	$\rightarrow x_2$	O	$\rightarrow a_2$	K_2	$\rightarrow K_2(T)$
n_{CO}	$\rightarrow x_3$	C	$\rightarrow a_3$	K_6	$\rightarrow K_3(T)$
n_{CO_2}	$\rightarrow x_4$	N	$\rightarrow a_4$	K_7	$\rightarrow K_4(T)$
n_{O_2}	$\rightarrow x_5$	$(Q_f)_i$	$\rightarrow b_i$	K_9	$\rightarrow K_5(T)$
n_{N_2}	$\rightarrow x_6$	$\Sigma n_j (Q_f)_j$	$\rightarrow b$	K_{10}	$\rightarrow K_6(T)$
n_{OH}	$\rightarrow x_7$	P_e	$\rightarrow p$	S_i^T	$\rightarrow M_i(T)$
n_{NO}	$\rightarrow x_8$	R	$\rightarrow R(1.9871)$	$(\Delta H_{300}^T)_i$	$\rightarrow L_i(T)$
n_O	$\rightarrow x_9$				
n_H	$\rightarrow x_{10}$				
σ	$\rightarrow \sigma$				
T	$\rightarrow T$				

[5] Numbers in parentheses indicate References at end of paper.

B Statement of Equations

We now have the following set of equations and symbols:

Variables: $x_1, x_2, \ldots, x_{10}, \sigma, T$
Constants: $b, p, R, a_1, \ldots, a_4, b_1, \ldots, b_{10}$
Parameters (tabulated at intervals of 100°): $K_1(T), \ldots, K_6(T), L_1(T), \ldots, L_{10}(T), M_1(T), \ldots, M_{10}(T)$

The chamber-conditions equations are as follows:

$$K_1(T) = \frac{x_3 x_5}{x_1 x_4} \quad [17]$$

$$K_2(T)\left(\frac{\sigma}{p}\right)^{\frac{1}{2}} = \frac{x_3 x_8}{x_2 x_6^{\frac{1}{2}}} \quad [18]$$

$$K_3(T)\left(\frac{\sigma}{p}\right) = \frac{x_1^2 x_5}{x_2^2} \quad [19]$$

$$K_4(T)\left(\frac{\sigma}{p}\right) = \frac{x_1 x_9}{x_2} \quad [20]$$

$$K_5(T)\left(\frac{\sigma}{p}\right)^{\frac{1}{2}} \frac{x_{10}}{x_1^{\frac{1}{2}}} \quad [21]$$

$$K_6(T)\left(\frac{\sigma}{p}\right)^{\frac{1}{2}} = \frac{x_7 x_1^{\frac{1}{2}}}{x_2} \quad [22]$$

$$a_1 = 2x_1 + 2x_2 + x_7 + x_{10} \quad [23]$$

$$a_2 = x_2 + x_3 + 2x_4 + 2x_5 + x_7 + x_8 + x_9 \quad [24]$$

$$a_3 = x_3 + x_4 \quad [25]$$

$$a_4 = 2x_6 + x_c \quad [26]$$

$$\sigma = \sum_{i=1}^{10} x_i \quad [27]$$

$$f_3(T) = f_1(T) - f_2(T) + b = 0 \quad [28]$$

where

$$f_1(T) = \sum_{i=1}^{10} x_i L_i(T)$$

$$f_2(T) = \sum_{i=1}^{10} b_i x_i$$

T_c represents the value of T, and σ_c represents the value of σ obtained from the simultaneous solution of Equations [17] through [28]

The frozen flow exit conditions equation is

$$T_e^{(n)} = \frac{T_c}{p \exp\left(\frac{q_{2-1}}{q_3}\right)} \quad [29]$$

where

$$q_1 = \frac{f_1(T_c) - f_1(T_e^{(n-1)})}{T_c - T_e^{(n-1)}} \times 10^3$$

$$q_2 = q_1 - \sigma_c R$$

$$q_3 = q_1/q_2$$

(Equation [29] yields a value for the nth iteration on T_e, and $T_e^{(0)}$ is the initial guess.)

The equation for the equilibrium-flow exit conditions is

$$f_6(T) = f_5(T_e) - f_4(T) - \sigma_e R \ln p = 0 \quad [28']$$

where

$$f_5(T) = f_4(T) - \sigma \sum_{i=1}^{10} \frac{x_i}{\sigma} R \ln \frac{x_i}{\sigma}$$

$$f_4(T) = \sum_{i=1}^{10} x_i M_i(T)$$

Working equations are as follows

$$x_2 = F(x_1, \sigma) = \frac{a_1 - 2x_1 - \left(\frac{\sigma}{p}\right)^{\frac{1}{2}} K_5(T) x_1^{\frac{1}{2}}}{2 + \frac{\left(\frac{\sigma}{p}\right)^{\frac{1}{2}} K_6(T)}{x_1^{\frac{1}{2}}}} \quad [30]$$

$$a_2 = g(x_1, x_2, \sigma) = a_2 + x_2 + \frac{a_3 x_2}{x_1 K_1(T) + x_2} + \left(\frac{\sigma}{p}\right)\frac{x_2}{x_1} K_4(T) + 2\left(\frac{\sigma}{p}\right)\left(\frac{x_2}{x_1}\right)^2 K_3(T) + \left(\frac{\sigma}{p}\right)^{\frac{1}{2}} \frac{x_2}{x_1^{\frac{1}{2}}} K_6(T) - \frac{1}{4}\left(\frac{\sigma}{p}\right)\left(\frac{x_2}{x_1}\right)^2 [K_2(T)]^2 + \frac{1}{2}\sqrt{\left[\frac{1}{2}\left(\frac{\sigma}{p}\right)\left(\frac{x_2}{x_1}\right)^2 \{K_2(T)\}^2\right]^2 + 2\left(\frac{\sigma}{p}\right) a_4 \left(\frac{x_2}{x_1}\right)^2 \{K_2(T)\}^2} \quad [31]$$

T_e represents either the limit of the iteration on $T_e^{(n)}$ in Equation [29] (for frozen flow) or the value of T obtained by the simultaneous solution of Equations [17] through [28] with [28] replaced by [28'] (for equilibrium flow); σ_e is the corresponding value of σ.

The following 12 equations are the performance parameter equations

$$\Delta H_{T_e}^{T_c} = [f_1(T_c) - f_1(T_e)] - [f_2(T_c) - f_2(T_e)] \quad [32]$$

$$c(\text{cm/sec}) = \left(\frac{2\Delta H_{T_e}^{T_c} \times 4.184}{m}\right)^{\frac{1}{2}} \times 10^3 \quad [33]$$

where m is in grams and $\Delta H_{T_e}^{T_c}$ is in kcal

$$c(\text{ft/sec}) = \frac{c(\text{cm/sec})}{30.48} \quad [34]$$

$$I_{sp} = \frac{c(\text{ft/sec})}{32.174} \quad [35]$$

$$\overline{M} = \frac{1}{2}\left(\frac{m}{\sigma_c} + \frac{m}{\sigma_e}\right) \quad [36]$$

$$\bar{\sigma} = \frac{1}{2}(\sigma_c + \sigma_e) \quad [37]$$

$$c_p = \frac{\Delta H_{T_e}^{T_c}}{\bar{\sigma}(T_c - T_e)} \quad [38]$$

$$\bar{c}_v = \bar{c}_p - R \quad [39]$$

$$\bar{\gamma} = \bar{c}_p/\bar{c}_v \quad [40]$$

$$\Gamma(\bar{\gamma}) = \frac{2}{\bar{\gamma} + 1}\left[\frac{\bar{\gamma} + 1}{2(\bar{\gamma} - 1)}\right]^{\bar{\gamma}^{\frac{1}{2}}} \quad [41]$$

$$c^* = \frac{299.5\left(\frac{T_c}{\overline{M}}\right)^{\frac{1}{2}}}{\Gamma(\bar{\gamma})} \quad [42]$$

$$c_F = \frac{c}{c^*} \quad [43]$$

Note: Equations [32], [33], [35], and [42] correspond, with the new notation, to Equations [13], [14], [15], and [16] in Section I.

C Description of the Method of Solution Used in the Existing Program

The desired solution consists of two lists of values for the variables on the left of Equations [33] through [43], one list for frozen-flow calculations, which we will call system 1, and one list for equilibrium-flow calculations, which we will call system 2. Sometimes other previously determined values may be desired; e.g., T_c, T_e, x_i, σ_c. System 1 consists of Equations [17] through [28], [29], and [32] through [43],

where T_e in Equation [29] is the T calculated in Equations [17] through [28]. System 2 consists of Equations [17] through [28] and [32] through [43], with Equation [28] replaced by Equation [28′] where T_c in Equation [28′] is T_c of system 1.

For computational purposes, Equations [17] through [26] are replaced by Equations [30] and [31].

With assumed values of σ and T, Equations [30] and [31] lead to values of x_1 and x_2 satisfying Equations [17] through [26]. (Note that some of the x_i appear implicitly as terms

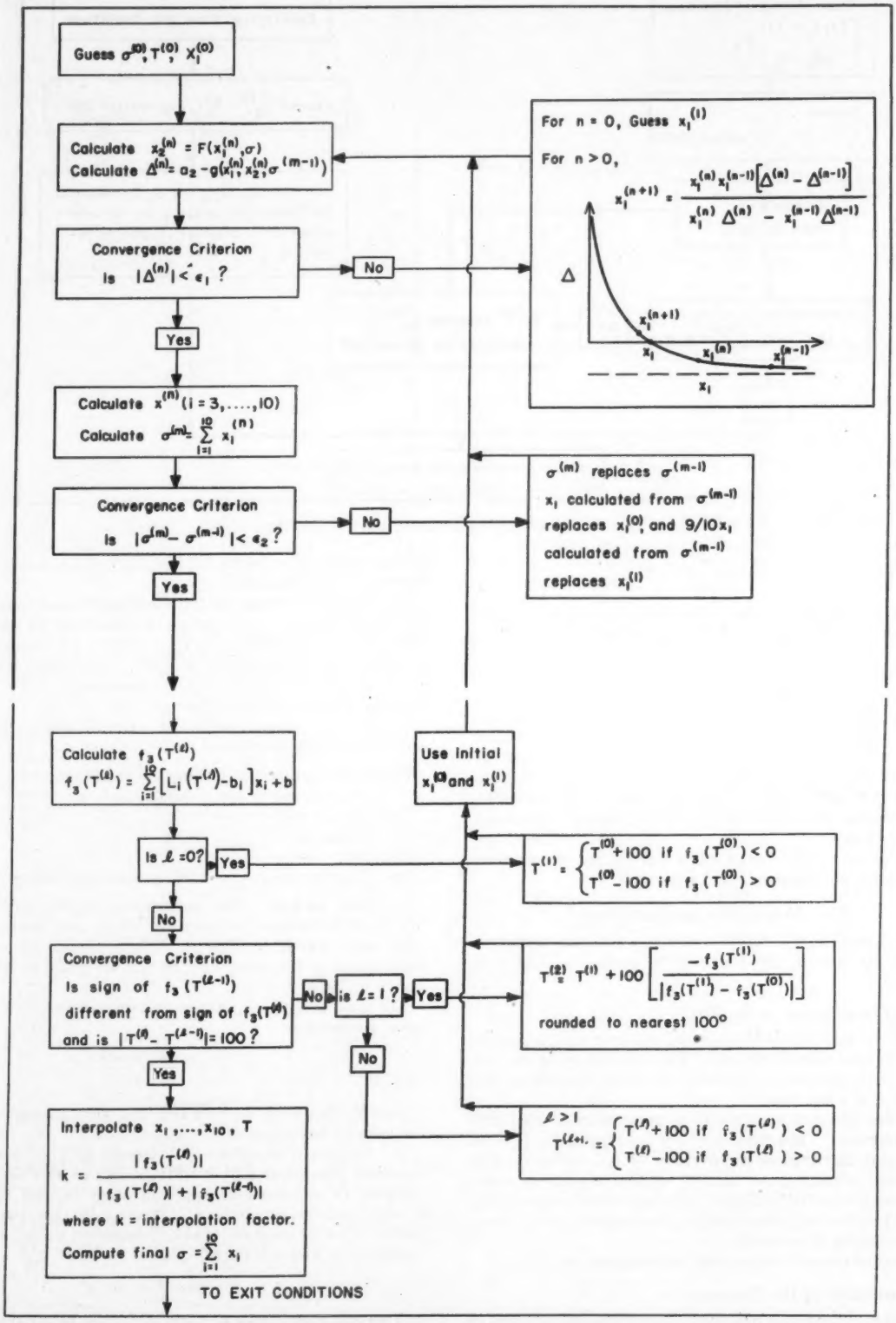
Guess $\sigma^{(0)}, T^{(0)}, x_i^{(0)}$
Calculate $x_2^{(n)} = F(x_1^{(n)}, \sigma)$
Calculate $\Delta^{(n)} = a_2 - g(x_1^{(n)}, x_2^{(n)}, \sigma^{(m-1)})$
Convergence Criterion
Is $|\Delta^{(n)}| < \epsilon_1$?
No
Yes
For n = 0, Guess $x_1^{(1)}$
For n > 0,
$x_1^{(n+1)} = \frac{x_1^{(n)} x_1^{(n-1)} [\Delta^{(n)} - \Delta^{(n-1)}]}{x_1^{(n)} \Delta^{(n)} - x_1^{(n-1)} \Delta^{(n-1)}}$
Calculate $x^{(n)}$ (i = 3, ..., 10)
Calculate $\sigma^{(m)} = \sum_{i=1}^{10} x_i^{(n)}$
Convergence Criterion
Is $|\sigma^{(m)} - \sigma^{(m-1)}| < \epsilon_2$?
No
Yes
$\sigma^{(m)}$ replaces $\sigma^{(m-1)}$
x_i calculated from $\sigma^{(m-1)}$
replaces $x_i^{(0)}$ and 9/10 x_i
calculated from $\sigma^{(m-1)}$
replaces $x_i^{(1)}$
Calculate $f_3(T^{(\ell)})$
$f_3(T^{(\ell)}) = \sum_{i=1}^{10} [L_i (T^{(\ell)}) - b_i] x_i + b$
Use initial
$x_i^{(0)}$ and $x_i^{(1)}$
Is $\ell = 0$?
Yes
No
$T^{(1)} = \begin{cases} T^{(0)} + 100 \text{ if } f_3(T^{(0)}) < 0 \\ T^{(0)} - 100 \text{ if } f_3(T^{(0)}) > 0 \end{cases}$
Convergence Criterion
Is sign of $f_3(T^{(\ell-1)})$
different from sign of $f_3(T^{(\ell)})$
and is $|T^{(\ell)} - T^{(\ell-1)}| = 100$?
No
is $\ell = 1$?
Yes
No
$T^{(2)} = T^{(1)} + 100 \left[\frac{-f_3(T^{(1)})}{|f_3(T^{(1)}) - f_3(T^{(0)})|} \right]$
rounded to nearest 100°
Yes
Interpolate $x_1, \ldots, x_{10}, T$
$k = \frac{|f_3(T^{(\ell)})|}{|f_3(T^{(\ell)})| + |f_3(T^{(\ell-1)})|}$
where k = interpolation factor.
Compute final $\sigma = \sum_{i=1}^{10} x_i$
$\ell > 1$
$T^{(\ell+1)} = \begin{cases} T^{(\ell)} + 100 \text{ if } f_3(T^{(\ell)}) < 0 \\ T^{(\ell)} - 100 \text{ if } f_3(T^{(\ell)}) > 0 \end{cases}$
TO EXIT CONDITIONS

Fig. 1a Diagram of cyclic structure of the problem

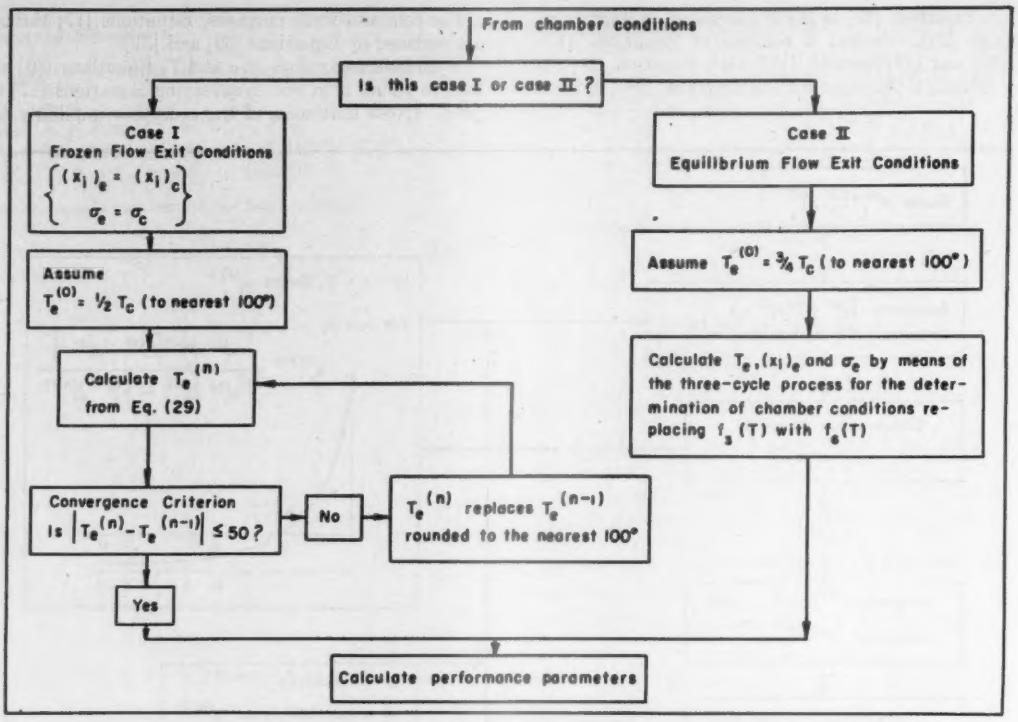
From chamber conditions
Is this case I or case II ?
Case I
Frozen Flow Exit Conditions
$(x_i)_e = (x_i)_c$
$\sigma_e = \sigma_c$
Case II
Equilibrium Flow Exit Conditions
Assume $T_e^{(0)} = \frac{1}{2} T_c$ (to nearest 100°)
Assume $T_e^{(0)} = \frac{3}{4} T_c$ (to nearest 100°)
Calculate $T_e^{(n)}$ from Eq. (29)
Calculate T_e, $(x_i)_e$ and σ_e by means of the three-cycle process for the determination of chamber conditions replacing $f_3(T)$ with $f_6(T)$
Convergence Criterion
Is $\left|T_e^{(n)} - T_e^{(n-1)}\right| \leq 50$?
No
$T_e^{(n)}$ replaces $T_e^{(n-1)}$ rounded to the nearest 100°
Yes
Calculate performance parameters

Fig. 1b Diagram of cylic structure of the problem

of Equation [31]; e.g. $x_9 = \left(\frac{\sigma}{p}\right) K_4(T) \frac{x_2}{x_1}$

The method of solution utilized by the program is essentially of a four-cycle structure and is schematically described in Figs. 1a, b.

The first cycle, which is referred to as the x_1 cycle, consists of repeated corrections to the guesses of x_i, assuming σ and T to be correct. The second cycle, which is referred to as the σ cycle, consists of repeated corrections to σ, assuming T to be correct. The σ cycle contains the x_1 cycles necessary to correct the x_i for the change in σ. The third cycle, which is referred to as the T cycle, consists of repeated corrections to T and contains the σ cycles (and x_1 cycles) necessary to correct σ for the changes in T (and to correct the x_i for the resulting changes in σ). The fourth cycle follows the three other cycles and is not interconnected with them.

IV Machine Computation

In this section, the solution of the previously described problem by use of the ElectroData computer (EDC) is discussed.

A Brief Description of the EDC

The EDC is a single-address, serial machine using a binary-coded, decimal-number system. The four bits of the decimal number are operated in parallel. A word consists of ten decimal digits and sign.

The machine uses a magnetic-drum memory divided into two hierarchies. The main memory has a capacity of 4000 words and an average access time of 8.5 millisec. The high-speed memory has a capacity of 80 words and an average access time of 0.85 millisec. The high-speed memory consists of four recirculating loops on the magnetic drum, each loop containing 20 words (2).

A detailed account of the commands is presented in (3).

B Description of the Program

Because of the cyclic nature of the calculations involved in the solution of this problem, it is convenient to divide the actual coding into separate sections, each of which is coded in the form of a subroutine.

The separate sections are: (a) Floating-decimal operations. (b) Table look-up. (c) Solution of Equations [17] through [27]. (d) Computation of $f_1(T)$ or $f_2(T)$. (e) Computation of $f_3(T)$. (f) Computation of $f_5(T)$. (g) Interpolation of x_i, T, $L_i(T)$ and $M_i(T)$. (h) Computation of $T_e^{(n)}$. (i) Solution of Equations [33] through [43].

1. *Floating-decimal operations.* The following floating-decimal subroutines are used in the problem:

(a) Floating-decimal arithmetic (addition, subtraction, multiplication, and division).
(b) Square root.
(c) Log x.
(d) 10^x.
(e) Floating-decimal to fixed-decimal conversion.

2. *Table look-up.* The parameters $K_s(T)$, $L_i(T)$, and $M_i(T)$ are tabulated at intervals of 100 K over the temperature range 300 K to 5000 K. These tabular values have been stored in two groups. The K_s, M_i group is stored as shown in Table 2.

For table look-up, α_n may be determined directly from T_n using the relation

$$\alpha_n = \alpha_1 + 17 \frac{T_n - 300}{100} \quad \text{[44]}$$

The K_s, L_i group has been stored in identical fashion, the only change being that M_i is replaced by L_i.

3. *Solution of Equations [17] through [27] using working equations (Equations [30] and [31]).* For given T and initial estimate of σ, successive approximations to that value of x_1 which satisfies Equations [17] through [26] are determined in the following manner: Let $x_1^{(n)}$ represent the n^{th} approximation to x_1, and $\Delta^{(n)}$ the n^{th} value of Δ where

$$\Delta = a_2 - g[x_1, F(x_1, \sigma), \sigma] \quad \text{[45]}$$

Two initial estimates $x_1^{(0)}$ and $x_1^{(1)}$ must be provided with the input data.

Substitution of $x_1^{(n)}$ into Equation [45] gives $\Delta^{(n)}$. When $\Delta^{(n)} = 0$, the value of $x_1^{(n)}$ is the value of x_1 which satisfies Equations [17] through [26].

It has been observed empirically that, in the region of convergence, the curve x_1 vs. Δ approximates a hyperbola of the form

$$\Delta = \frac{a}{x_1} + b \quad \ldots\ldots [46]$$

Table 2

Address	Stored value	Address	Stored value
α_1	$K_1(300°)$	α_n	$K_1(T_n)$
$\alpha_1 + 1$	$K_2(300°)$	.	$K_2(T_n)$
.	.	.	.
.	.	.	.
.	.	.	.
.	$K_6(300°)$	.	$K_6(T_n)$
.	$M_1(300°)$	.	$M_1(T_n)$
.	.	.	.
.	.	.	.
.	.	.	.
.	$M_{10}(300°)$	.	$M_{10}(T_n)$
$\alpha_1 + 16$	$T\ (300)°$	$\alpha_n + 16$	T_n
α_2	$K_1(400°)$	α_{48}	$K_1(5000°)$
$\alpha_2 + 1$	$K_2(400°)$	.	$K_2(5000°)$
.	.	.	.
.	.	.	.
.	.	.	.
.	$K_6(400°)$	.	$K_6(5000°)$
.	$M_1(400°)$	.	$M_1(5000°)$
.	.	.	.
.	.	.	.
.	.	.	.
.	$M_{10}(400°)$	.	$M_{10}(5000°)$
$\alpha_2 + 16$	$T\ (400°)$	$\alpha_{48} + 16$	T 5000°

Where $T_n = 300 + 100\ (n - 1)$ and $\alpha_n = \alpha_1 + 17\ (n - 1)$, where $n = 1, 2, \ldots, 48$.

Accordingly, a recurrence formula has been derived by solving the following three hyperbolic equations for $x_1^{(n+1)}$ in terms of $x_1^{(n)}$, $x_1^{(n-1)}$, $\Delta^{(n)}$, and $\Delta^{(n-1)}$, with the condition that $\Delta^{(n+1)} = 0$. Thus

$$\Delta^{(n-1)} = \frac{a}{x_1^{(n-1)}} + b \quad \ldots\ldots [47]$$

$$\Delta^{(n)} = \frac{a}{x_1^{(n)}} + b \quad \ldots\ldots [48]$$

$$\Delta^{(n+1)} = \frac{a}{x_1^{(n+1)}} + b \quad \ldots\ldots [49]$$

From Equations [47] and [48]

$$-\frac{a}{b} = \frac{x_1^{(n)} x_1^{(n-1)} [\Delta^{(n)} - \Delta^{(n-1)}]}{x_1^{(n)} \Delta^{(n)} - x_1^{(n-1)} \Delta^{(n-1)}} \quad \ldots\ldots [50]$$

From Equation [49], when $\Delta^{(n+1)} = 0$

$$-\frac{a}{b} = x_1^{(n+1)} \quad \ldots\ldots [51]$$

Equations [50] and [51] give the recurrence formula

$$x_1^{(n+1)} = \frac{x_1^{(n)} x_1^{(n-1)} [\Delta^{(n)} - \Delta^{(n-1)}]}{x_1^{(n)} \Delta^{(n)} - x_1^{(n-1)} \Delta^{(n-1)}} \quad \ldots\ldots [52]$$

The value of x_2 satisfying Equations [17] through [26] is given by $F(x_1, \sigma)$, and the values of the remaining x_i are obtained by direct substitution.

Equation [27] is then used to determine a new estimate for σ and the process is repeated. When the new estimate for σ is the same as the previous estimate, Equations [17] through [27] have been solved. A flow chart describing the logical and computational content of the subroutine just described appears in Fig. 2.

4. *Computation of $f_1(T)$ or $f_2(T)$, computation of $f_3(T)$, and computation of $f_5(T)$.* These sections, although not suffi-

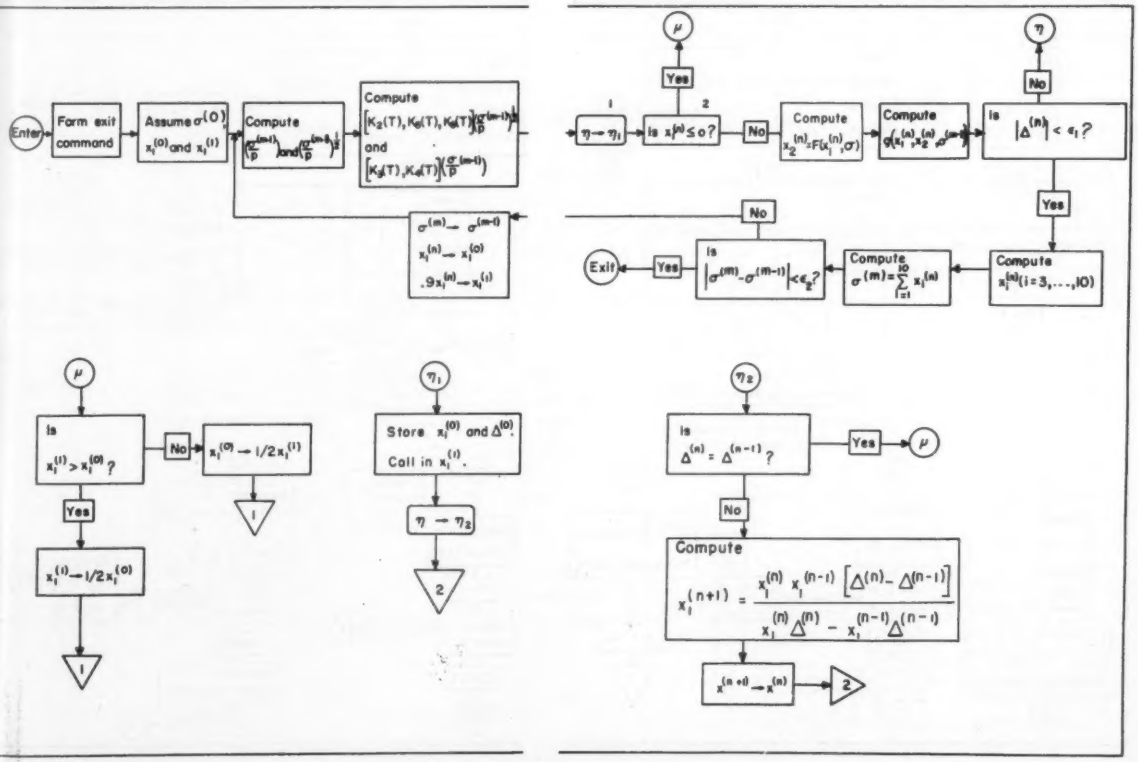

Fig. 2 Flow diagram of subroutine *c*

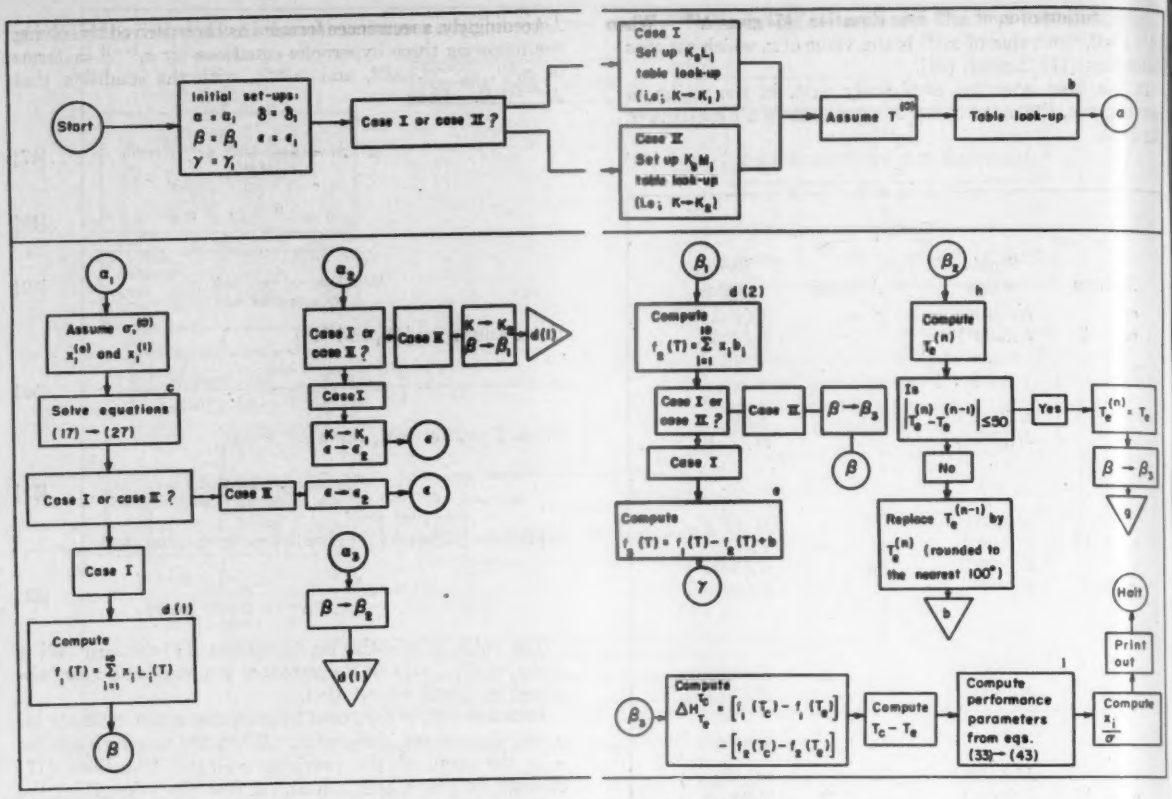

Fig. 3a Flow diagram of control program

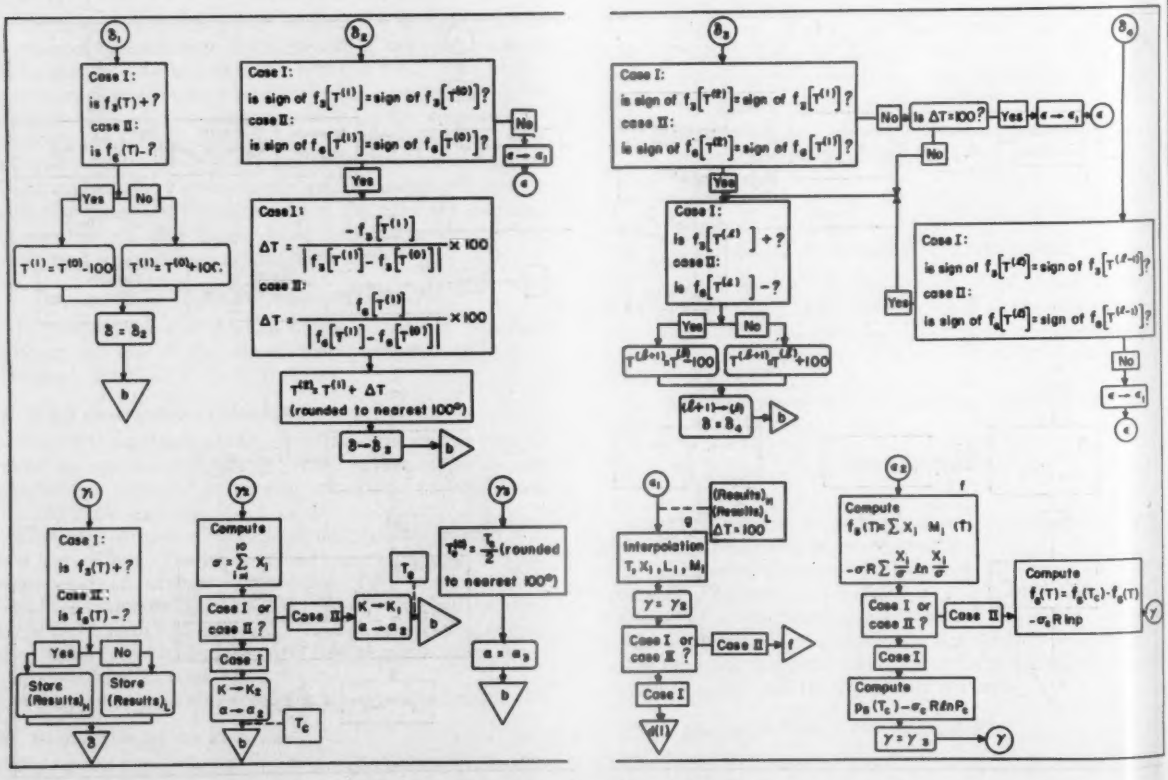

Fig. 3b Flow diagram of control program

ciently complex to warrant elaboration of detail, are coded separately because of the frequent and intermittent need for their use.

5. *Interpolation.* When two solutions for Equations [17] through [27] have been found for temperatures that differ by an interval of 100 K, such that $f_3(T^{(i)})$ and $f_3(T^{(i-1)})$ or $f_4(T^{(i)})$ and $f_6(T^{(i-1)})$ are opposite in sign, the final values for T and x_t and the values of L_t and M_t corresponding to the final x_t may be calculated with sufficient accuracy by means of linear interpolation. The final value for σ may then be calculated from the final x_t.

The interpolation section is divided into three subroutines:

(a) Computation of the interpolation factor k

$$k = \frac{|f_3(T^{(i)})|}{|f_3(T^{(i)})| + |f_3(T^{(i-1)})|} \text{ or } k = \frac{|f_6(T^{(i)})|}{|f_6(T^{(i)})| + |f_6(T^{(i-1)})|} \quad \ldots\ldots [53]$$

(b) Interpolation of T and x_t

(c) Interpolation of L_t and M_t

These three subroutines of the interpolation process are coded separately because they are not always used together.

6. *Computation of* $T_e^{(n)}$. This subroutine simply calculates $T_e^{(n)}$ using Equation [29].

7. *Solution of Equations [33] through [43].* Given T_c, T_e, ϵ_t, σ_c, $\Delta H_{T_e}^{T_c}$, this subroutine computes the performance parameters from Equations [33] through [43].

Control Program

Fig. 3 contains a complete flow diagram showing in detail the logical content of the control program. The sections listed above appear as separate boxes on the flow diagram and are identified by the letter by which they are listed. Case I in the diagram refers to the series of calculations including chamber conditions, frozen-flow exit conditions, and frozen-flow performance parameters. Case II refers to the calculation of equilibrium-flow exit conditions and equilibrium-flow performance parameters.

Modifications

A new program for solution of thermochemical problems is currently being developed at the Jet Propulsion Laboratory that incorporates several significant improvements over the program described in this paper. One such improvement is the introduction of a method for more rapid convergence of the x_t, σ, and T cycles. Another improvement is the elimination of table storage by means of approximating functions for the enthalpy and entropy curves. The equilibrium constants will be calculated directly from the enthalpy and entropy values. The new program will include equilibria for C, H, O, N plus some additional elements.

V Conclusion

The advantages of using a digital computer for the solution of thermochemical problems are very great. The improvements discussed in Section IV-C will soon be carried out. Furthermore, the extension of the program to include additional equilibria will considerably increase the usefulness of the code.

References

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ARS Meetings Calendar

		ARS Sessions	Send abtracts to	Abstracts Due
Mar. 14–16	ASME Aviation Conference Hotel Statler Los Angeles	Satellites Thermal thicket Air cargo	.....	.....
May 23–25	ASME-Engineering Institute of Canada Mount Royal Hotel, Montreal	Guided missiles	ARS National Office	.....
June 17–21	ARS-ASME Semi-Annual Meeting Hotel Statler Cleveland	Liquid rockets Solid rockets Ramjets Satellites	Henry C. Burlage Case Institute of Technology 10900 Euclid Avenue Cleveland 6, Ohio	.....
Sept. 17–21	Seventh IAF Congress Rome	Astronautics	ARS National Office	Apr. 1, 1956
Sept. 24–26	ARS Fall Meeting Buffalo	Propellants Combustion Telemetering	Ralph Bloom Becco Chem. Div. Food Mach. & Chem. Corp. Buffalo, N. Y.	Apr. 1, 1956
Nov. 25–30	ARS-ASME Annual Meeting New York	General	ARS National Office	May 15, 1956

Experiments on the Burning of Single Drops of Fuel[1]

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Experiments have been performed in order to measure the mass rate of consumption of single drops of liquid fuel suspended on a quartz filament and burning under various ambient conditions. The influence of increased oxidizer concentration, increased pressure, and elevated temperature in the surrounding atmosphere on mass burning rate has been studied. Comparison is made with theoretical calculations based on the concept of a heterogeneous diffusion flame, with burning rate controlled by heat and mass transfer. The influence of forced convection on burning rate and extinction of burning has also been investigated.

Nomenclature

K' = evaporation constant
d = drop diameter
r_e/r_l = ratio of flame radius to drop radius
T_0 = ambient temperature
T_e = flame temperature
$Y_{O,0}$ = weight fraction of oxidizer in ambient atmosphere

I Introduction

IN A previously published paper (1),[3] a theory for the burning of single fuel droplets in oxidizing atmospheres was presented. It is assumed in this theory that burning takes place at a spherical surface surrounding the droplet. The radius of this surface is determined by the rates of diffusion of the fuel vapor outward and the oxidizer inward toward the surface, using the assumption that the reaction surface is located at a point where the rates of delivery of fuel vapor and oxidizer are in stoichiometric proportions. The temperature of this flame surface is determined by heat balance considerations, and the burning rate, or evaporation rate, of the droplet is determined by the rate of heat transfer to the drop surface from the hot flame surface.

The theory predicts that the mass burning rate of a fuel droplet is proportional to the droplet diameter. This result is in agreement with experimental measurements (2, 3, 4) made of the burning rates of hydrocarbon fuel droplets in air. If the mass burning rate of a droplet is proportional to droplet diameter, then the diameter vs. time history of a burning droplet may be represented by the following equation:

$$d^2 = d_0^2 - K't \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where d is drop diameter, d_0 is the original drop diameter, t is time after ignition, and K' is a constant, independent of drop size and characteristic of the fuel-oxidizer system under consideration. The value of this constant, usually called the evaporation constant, therefore provides a convenient comparison between the burning rates of droplets of various fuels for arbitrary droplet sizes.

The afore-mentioned theory for droplet burning yields explicit expressions for the flame temperature, the flame radius, mass burning rate, and evaporation constant, K'.

In Ref. (1), theoretical values of K' as calculated for several pure hydrocarbon fuels burning in air at room temperature and atmospheric pressure were compared to the experimental results of Godsave (2), who measured the burning rates of droplets suspended on a quartz fiber. In spite of the approximations used in this idealized theory of droplet burning, the calculated burning rates were found to be in good agreement with the experimental data. It should be noted, however, that the burning rates did not vary widely for the various fuels that were tested, and therefore this comparison is not as stringent a test of the theory as might be desired.

In order to provide additional information on the burning of drops of pure hydrocarbon fuels under various atmospheric conditions, experiments have been performed on the effects of variation of composition, pressure, and temperature in the surrounding atmosphere, and on the influence of forced convection on the burning rates of suspended fuel droplets. The results of these tests are reported in the following sections.

II Combustion Apparatus

In order to provide means for experiments on burning of fuel drops under various conditions of temperature and pressure, a large combustion chamber has been constructed in the Mechanical Engineering Laboratory at the California Institute. The chamber is made of stainless steel, and consists of a thick-walled vertical tube, approximately 42 inches long and

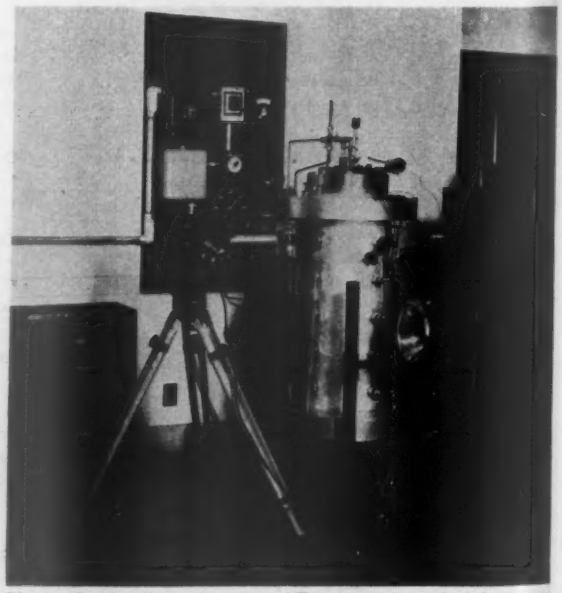

Fig. 1 Combustion apparatus. "Eyemo" camera in left center. Injection and ignition equipment visible on head of combustion tank

Presented at the ARS Fall Meeting, Los Angeles, Calif., Sept. 18–21, 1955.

[1] Supported by the O.O.R. under Contract DA04-495-Ord-446, Dept. of the Army Project No. 599-01-004, Ordnance Research and Development Project No. TB 2-001, O.O.R. Project No. 834. Abstracted from a thesis submitted by the author to the Graduate School of the California Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, June 1955. The author is happy to express his appreciation to Dr. S. S. Penner for helpful discussions.

[2] Engineer; present address, The RAND Corporation, Santa Monica, Calif. Mem. ARS.

[3] Numbers in parentheses indicate References at end of paper.

7 inches in inside diameter. A group of twelve electrical heating elements are mounted in the walls of the tube, and heavy thermal insulation covers the outside tube wall to decrease heat loss. A thermostatic control permits the temperature of the gas within the tube to be varied from room temperature up to 1000 F.

Ten quartz windows, $^3/_4$ inch thick and $2^1/_2$ inches in diameter, are mounted in the walls of the tank to provide for visual or photographic observation. The windows are arranged in two vertical rows of five each, diametrically opposed.

Five thermocouple wells, each at the level of one of the window groups, permit the determination of the internal gas temperature by use of iron-constantan thermocouples.

Heavy flanges are welded to the top and bottom of the tube, and are provided with studs and O-ring grooves so that the top and bottom of the tank may be easily removed. Various items of equipment such as fuel injectors or ignition equipment may then be mounted in the tank head, and can be easily removed for adjustment. The tank is further provided with pipe leads to allow for pressurization or addition of various gases.

A heavy camera stand is mounted adjacent to the tank to provide an adjustable, vibrationless support for motion picture equipment used to photograph the burning fuel droplets, which were suspended on a fine quartz filament. The filament and its support were mounted within the combustion tank described in the previous paragraph. A photograph of the tank, with its auxiliary apparatus, is shown in Fig. 1.

A fuel injection system was built into the head of the combustion tank. This system was provided with a fuel reservoir and means for pressurizing the reservoir. The fuel system was connected through a ball check valve to a hollow needle which extended approximately eight inches down into the tank.

A fine silica filament was cemented to the hollow needle and was of such a length that its tip extended vertically down so as to be in the line of sight of the top windows of the tank. It was necessary to thicken the end of the filament in order to retain the liquid drop. The diameter of the thickened end was approximately 0.3 mm.

Fig. 2 Droplet of ethyl alcohol burning in mixture of fifty per cent oxygen and fifty per cent nitrogen by weight

The drops were suspended on the filament by pressurizing the reservoir, thereby forcing fuel through the hollow needle and onto the silica filament. The suspended drops were found to be between 1.5 and 1.8 mm in diameter. As can be seen from Fig. 2, the suspended drops were reasonably spherical during the major part of their life.

The suspended drops were ignited by means of an electric spark. A standard automotive ignition circuit was utilized, with a manually operated on-off switch taking the place of the distributor breaker points.

An electrically driven 35-mm motion picture camera was used to photograph the burning drops, which were illuminated in silhouette by providing strong back lighting. A long focal length lens mounted on the camera with an extension tube provided a magnification of about two diameters on the film.

The drops were photographed at a camera speed of about twenty-four frames per second. The exact camera speed was determined by photographing a calibrated stop watch.

A $^3/_{32}$ inch diameter ball bearing was photographed at the beginning and end of each 100-foot roll of film used. This calibration was carried out under the same camera focusing conditions as for the burning drops, thereby providing an accurate reference length on the film for determining the actual size of the droplets.

The size of the burning drops was determined by using a technique very similar to that described by Godsave (2). The image on the film was measured with the aid of a 35-mm microfilm reader (to produce further magnification). Two measurements were made on each frame, namely, the two perpendicular diameters inclined at 45 deg to the major and minor axis of the elongated drop. The mean of these two measurements was recorded as the "effective diameter" of the drop. If the major and minor axes do not differ greatly, as was the case in these tests, then it is easily shown that the volume of a sphere with the measured effective diameter is not greatly different from that of the prolate spheroid which actually corresponds to the shape of the drop.

III The Effect of Varying Oxidizer Concentration

The first set of experiments in this investigation were performed to study the change of droplet burning rates as the oxygen concentration was varied in the oxygen-nitrogen mixture surrounding the suspended droplets (5). A systematic study was made to determine the evaporation constant, K'; for different oxygen concentrations and for the following fuels: n-heptane, ethyl alcohol, benzene, and toluene. The experimental results gave directly the droplet diameter, d, as a function of the time, t. The plots of d^2 against t were found to be linear. A typical experimental plot is shown in Fig. 3. Thus the functional relation between drop diameter d and time t, $d^2 = d_0^2 - K't$, has been verified again. Here d_0 is the diameter at time $t = 0$ (corresponding to the beginning of steady burning) and K' is the evaporation constant. The

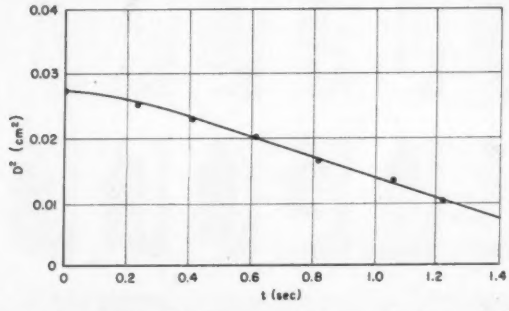

Fig. 3 Experimental plot of square of diameter (D^2) vs. time (t) for an ethyl alcohol droplet burning in oxygen-nitrogen mixture ($Y_{O,0} = 0.5$)

Table 1 Experimental values of K' (cm²/sec) for several fuels and weight fractions of oxygen

(Weight fractions of oxygen ($Y_{O,0}$)

Fuel	$Y_{O,0} = 0.23$	$Y_{O,0} = 0.37$	$Y_{O,0} = 0.50$	$Y_{O,0} = 0.70$	$Y_{O,0} = 0.90$
n-heptane	8.4×10^{-3}	13.8×10^{-3}	15.0×10^{-3}	18.6×10^{-3}	22.3×10^{-3}
Ethyl alcohol	8.6×10^{-3}	11.1×10^{-3}	15.0×10^{-3}	18.4×10^{-3}	20.4×10^{-3}
Benzene	9.9×10^{-3}		residue formation		
Toluene	7.7×10^{-3}		residue formation		

value of K' is determined directly from the slope of plots of d^2 vs. t and has the dimensions $cm^2 - sec^{-1}$.

The experimentally determined values of K' for the four fuels tested at different oxygen weight fractions are listed in Table 1. The results of five separate experiments were examined for each fuel at each value of $Y_{O,0}$. The tabulated values of the evaporation constant are the mean values for each set of five runs. The reproducibility in each set of runs was good; the maximum spread of experimental data was found to be less than ± 1 per cent.

With the lighting used for photography during the experiments, it was impossible to obtain pictures of the flames suitable for measurement of flame surface diameter. For n-heptane and ethyl alcohol the luminous flame surface was not sufficiently well-defined to permit conclusions regarding flame shape and flame size. For benzene and toluene burning in air, the luminous region could be seen but was not sufficiently clear to yield accurate measurements.

For oxygen weight fractions exceeding 23 per cent, formation of residue was observed during the burning of benzene and toluene. Photographs of droplets of benzene burning in atmospheres of various oxygen weight fractions are shown in Fig. 4. The residue remaining on the filament at the conclusion of combustion was of dry, brittle consistency. No chemical analysis of the residue was made. The formation of carbon in heterogeneous combustion of aromatic hydrocarbon fuels has been observed by other investigators and merits additional quantitative study.

Because of residue formation during the burning of benzene and toluene, it was impossible to determine accurately the burning rates of these fuels. The shroudlike formation of residue caused considerable distortion of the drop, and often completely surrounded and obscured the drop of fuel.

Carbon formation during the heterogeneous combustion of aromatic fuels, but not during the burning of aliphatic compounds, re-emphasizes the importance of chemical reaction rates, which have been neglected in the diffusion model for droplet burning. According to one of the modern theories for carbon formation during burning (6), acetylene production is an essential intermediate step. One might therefore argue that the greater tendency of aromatic fuels to form carbonaceous residues is related to the known ease with which these compounds form acetylene. This qualitative suggestion does not offer a satisfactory explanation for the dependence of residue formation on oxygen concentration.

A possible explanation for this variation in residue formation is the following: as the oxygen concentration is increased, the temperature of the flame zone becomes higher and tends to increase pyrolysis of the aromatic fuel. The lighter compounds and radicals (e.g., acetylene) thereby produced then polymerize in the cooler tip of the flame. This process continues until the burning droplet is extinguished because of the growth of the residue. If the oxygen concentration is further increased, the residue formed is itself capable of being burned, although at a slower rate than the liquid fuel. The consumption of the residue may be noted in the two bottom rows of photographs in Fig. 4.

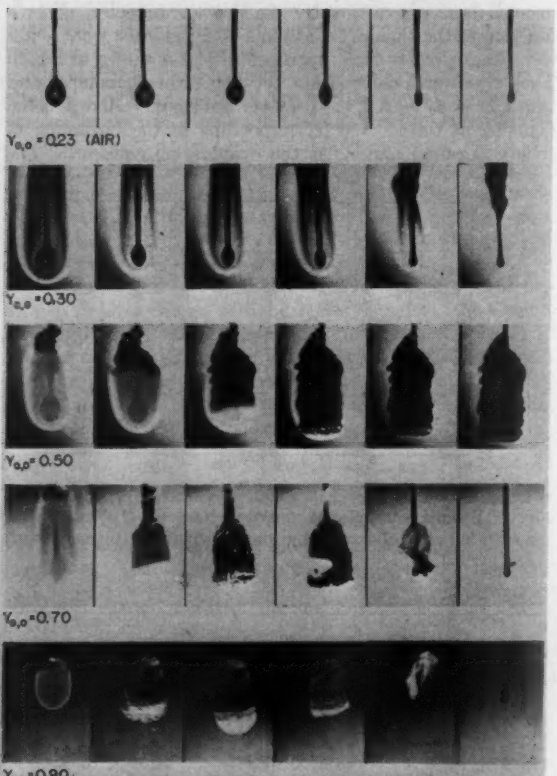

Fig. 4 Benzene droplets burning in various oxygen-nitrogen mixtures showing residue formation

IV The Effect of Ambient Pressure on Burning Rate

The influence of increased atmospheric pressure on the burning rates of droplets of various hydrocarbons burning in air has been investigated by Hall and Diederichsen (7). In their experiments, suspended droplets of furfuryl alcohol, tetralin, decane, and amyl acetate were burned in air at pressures ranging from one to twenty atmospheres. Again, the measurements showed that the mass burning rate of a droplet is proportional to the drop diameter.

The data for furfural alcohol and tetraline indicate that the burning rate, or K', is proportional to the pressure raised to the 0.2 power; data for decane and amyl acetate indicate that burning rate is proportional to pressure raised to the 0.3 power. Hall and Diederichsen conclude that the mass burning rate is roughly proportional to the one-fourth power of the pressure for hydrocarbons burning in air.

They also studied the size and shape of the flame front surrounding the liquid droplets. In contrast to the data of Godsave (2), which indicated that the ratio of flame to drop size is a constant, Hall and Diederichsen report that it was the distance between the flame front and the drop surface that appeared to be constant during burning.

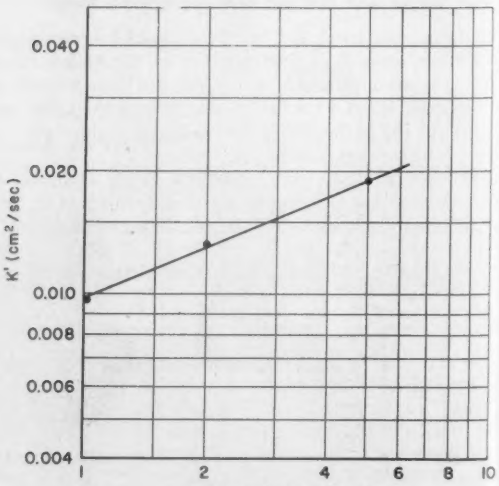

Fig. 5 Variation of evaporation constant (K') with pressure for benzene burning in air

Primarily in connection with the residue formation behavior exhibited by some aromatic fuels, as reported in the last section, it was thought desirable to study the influence of air pressure on the burning behavior of drops of benzene, a typical aromatic. Owing to the limitations of the spark ignition method, data were obtained only up to a pressure of five atmospheres.

The results of these experiments are shown in Fig. 5, where log K' is plotted against log P. Reference to Fig. 5 shows that the burning rate of benzene drops in air is roughly proportional to the 0.4 power of the pressure. No residue formation in excess of that found for burning at atmospheric pressure was noted at the higher pressures.

V Effect of Increased Ambient Temperature on Drop Burning Rates

Another parameter of interest in its effect on droplet burning rate is the temperature of the surrounding oxidizing atmosphere. In his investigations of the rate of evaporation of droplets suspended in a hot gas, Kobayasi (8) found that at ambient temperatures of about 700 C, hydrocarbon drops underwent autoignition. Therefore, in a further investigation (9), Kobayasi measured the mass burning rates of droplets burning in air at temperatures up to 900 C. Again it was found that mass burning rate is proportional to drop diameter.

The experimental technique used by Kobayasi utilized the suspension of the droplet on a quartz fiber outside the combustion chamber. The heated chamber was mounted on rails, and was then moved over the drop and its suspending fiber. Motion pictures were taken of the burning droplet through windows in the chamber walls. Mass burning rates could then be calculated from the decrease in size of the drop image with time. Kobayasi's data show considerable scatter. His results for two fuels, n-heptane and benzene, are listed in Table 2.

Table 2 Experimental values of K' (cm²/sec) for two fuels burning in air at elevated temperature (Kobayasi, Ref. (9))

n-Heptane		Benzene	
T_0(°C)	K'(cm²/sec)	T_0(°C)	K' (cm²/sec)
700	0.0121	710	0.0100
	0.0110		0.0122
800	0.0124	730	0.0105
			0.0108
			0.0090
		735	0.0101
		750	0.0087
			0.0091
			0.0096
			0.0111
		800	0.0116
			0.0137

In order to provide data for temperatures intermediate between room temperature and the high temperatures reported in Kobayasi's work, measurements of burning rates have been made in the course of the present investigation.

Data were obtained for the burning rates of benzene and n-heptane at temperatures of about 140 C (300 F). At somewhat higher temperatures it was found that the droplets would not adhere to the quartz fiber and fell off as soon as they were formed. At still higher temperatures, the liquid fuel was vaporized while flowing through the hypodermic needle; hence no drops could be formed.

For these reasons, only a limited amount of data could be obtained using this injection device. Also, owing to the discrepancy between these data and the results of other investigations (see Figs. 9 and 10), even the limited data obtained are subject to question. A possible explanation for the discrepancy may be that an appreciable amount of the heat necessary to evaporate the liquid fuel may have been supplied from the hot quartz fiber. An attempt was made to reduce this error by flowing a stream of the liquid fuel over the quartz fiber before suspending the droplet whose burning rate was studied.

A summary of the data obtained in these tests is presented in Table 3. In contrast to the highly reproducible data obtained in the experiments reported in Section III, considerable scatter was found in the present case.

Table 3 Experimental values of K' (cm²/sec) for two fuels burning in air at elevated temperature

n-Heptane		Benzene	
T_0(°C)	K' (cm²/sec)	T_0(°C)	K' (cm²/sec)
135	0.0115	150	0.0123
	0.0116		0.0144
	0.0115		0.0120
	0.0116		0.0129
	0.0111		0.0130
	0.0110		0.0130

VI Effect of Forced Convection on Drop Burning Rates

All of the experiments described thus far have been performed with droplets burning in a quiescent atmosphere, subject only to the effects of free convection. It was therefore thought to be of interest to investigate the influence of forced convection on a burning droplet. In order to obtain an accurate quantitative description of droplet burning rates as a function of the physico-chemical parameters and the flow conditions, an extensive experimental program would be necessary. The effort involved in such an elaborate investigation precluded its inclusion in the present program.

However, a more modest series of experiments was performed in order to answer two important questions concerning the effects of forced convection. These questions are: (1) What is the order of magnitude of change of burning rate caused by forced convection? (2) At what gas velocity is the flame surrounding the droplet extinguished, i.e., "blown off?" A description of these experiments and of the results will now be presented.

The large combustion tank was not used for experiments on the influence of forced convection on burning rate. Instead, the droplets were suspended on a quartz fiber in a small duct through which air could be blown. The duct was constructed of lucite tubing, two inches in inside diameter and approximately one foot long. The duct was held vertically with the air flowing upward. The air was introduced at the bottom of the duct, and flowed through two baffle plates and three fine screens before passing over the drop. The purpose of the baffle plates and screens was to insure a fairly flat velocity profile across the diameter of the duct.

The air flow was metered by a Fischer and Porter Laboratory Flowrator. The linear air velocity in the duct was obtained by dividing the volume flow rate by the cross-sectional area of the duct.

A quartz fiber was inserted downward into the exit of the duct. The droplets were suspended on the tip of the fiber by means of a hypodermic syringe. Again, ignition was accomplished by means of an electric spark. The motion picture equipment previously described was used to photograph the burning of the droplets.

Droplet diameter vs. time histories were obtained for n-

heptane, ethyl alcohol, and benzene burning in air streams of velocities up to 40 cm/sec. In order to obtain the functional dependence of droplet burning rate on the flow parameters (e.g., Reynolds number) from a set of diameter vs. time plots, data sufficiently accurate to define the second derivative of the droplet diameter vs. time curve are necessary. The present experimental technique does not yield sufficiently accurate diameter histories to permit this type of analysis. Instead, the method of analysis used for the still atmosphere experiments was employed, where the square of the droplet diameter was plotted as a function of time. Data for a still atmosphere (except for free convection currents) yielded straight line plots when presented in this way; the present data, on the other hand, showed irregular, but relatively small, deviations.

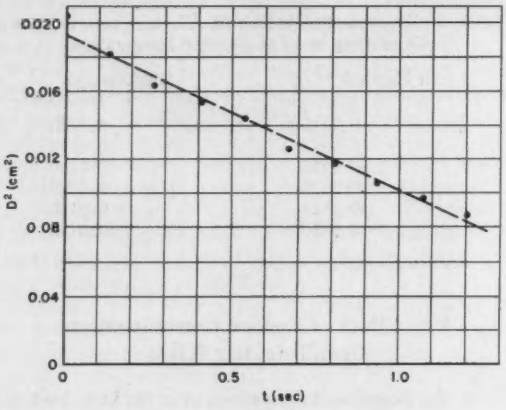

Fig. 6 Experimental plot of square of diameter (D^2) vs. time (t) for an ethyl alcohol drop burning in air stream of 11.8 cm/sec velocity

A typical plot is shown in Fig. 6. Although it was not proved that the mass rate of fuel consumption is accurately proportional to the drop diameter under conditions of forced convection, it was possible to fit a straight line to the plots of d^2 vs. t and, therefore, to obtain an effective value for K', the evaporation constant. The values for the effective evaporation constants evaluated in this way are presented in Table 4. Each value reported is the average of values found for three separate runs. The individual values varied from the average value by no more than ± 5 per cent.

It is seen that the droplet burning rates, as represented by the effective evaporation constant, are increased up to a maximum of thirty-six per cent at the highest gas velocities used in these tests. At gas velocities higher than the largest values shown in Table 4, the burning droplets were extinguished. It may be seen that these velocities are quite low, in no case exceeding 40 cm/sec.

Spalding (10) has investigated the flame blow-off phenomenon for porous spheres covered by a liquid film of fuel.

Table 4 Effective values of the evaporation constant, K' for n-heptane, ethyl alcohol, and benzene droplets burning in an air stream

Fuel	Air velocity (cm/sec)	Effective K' (cm^2/sec)	Effective K'/still air K'
n-Heptane	0	8.4×10^{-3}	1.00
	11.8	10.2	1.22
	26.9	11.0	1.32
	34.5	11.4	1.36
Ethyl alcohol	0	8.6×10^{-3}	1.00
	11.8	9.0	1.05
	26.9	9.6	1.12
	39.4	10.7	1.25
Benzene	0	9.9×10^{-3}	1.00
	11.8	10.4	1.06
	26.9	11.5	1.17
	34.5	13.1	1.33

The spheres were immersed in an air stream. He reports that as the air velocity was increased, the flame that had heretofore surrounded the sphere was altered so as to burn only behind the sphere. The flame remained attached to the surface, however, and resembled the flame front observed for the case of cylindrical flameholders in a stream of premixed fuel and air. At still higher velocities, Spalding reports that the flame burned in the wake of the sphere and was not attached to the surface. This progression of blow-off phenomena was not observed in the present investigation of droplet burning.

It is quite likely that the supporting quartz fiber may exert considerable influence on the flame blow-off behavior. For this reason it would be advisable to study blow-off by the use of droplets falling freely through the oxidizing gas.

VII Comparison of Theory and Experiment

As has been previously noted, the results of the droplet combustion theory have been compared to the experimental data of Godsave in (2). The burning rates were found to be in satisfactory agreement. The calculated and observed values of the combustion radius, r_c, were also compared. The calculated values are considerably in excess of the observed values, and reasons for this discrepancy were noted.

A Effect of Increasing Oxygen Concentration

In Table 5, the values of K', T_c, and r_c/r_l as computed by the diffusion theory are presented for n-heptane and ethyl alcohol burning in various oxygen-nitrogen mixtures. As would be expected, the flame temperatures rise with increasing oxygen concentration, while the ratio of flame radius to drop radius decreases. The extremely high computed flame temperatures result directly from the fact that the effects of

Table 5 Calculated values for drops of n-heptane and ethyl alcohol burning in various oxygen-nitrogen mixtures according to the diffusion theory

	$Y_{O,0} = 0.10$	$Y_{O,0} = 0.23$	$Y_{O,0} = 0.37$	$Y_{O,0} = 0.50$	$Y_{O,0} = 0.70$	$Y_{O,0} = 0.90$
n-heptane						
T_c(°K)	1694	3225	4555	5575	6810	7755
r_c/r_l	19.02	8.58	4.51	3.88	2.91	2.39
K'(cm^2/sec)	4.85×10^{-3}	8.58×10^{-3}	12.35×10^{-3}	14.58×10^{-3}	18.52×10^{-3}	22.50×10^{-3}
Ethyl alcohol						
T_c(°K)	1687	3110	4280	5110	6080	6780
r_c/r_l	8.70	5.30	3.62	2.82	2.30	1.99
K' (cm^2/sec)	3.88×10^{-3}	7.91×10^{-3}	11.64×10^{-3}	14.95×10^{-3}	19.47×10^{-3}	24.00×10^{-3}

dissociation have been neglected in the theoretical analysis. In spite of these unrealistic calculated flame temperatures, the calculated values of the evaporation constant, K', are found to be in satisfactory agreement with the experimentally determined values. A graphical comparison of experimental and theoretical values of K' is made in Figs. 7 and 8, where values of K' for n-heptane and ethyl alcohol are plotted as a function of $Y_{O,\infty}$, the weight fraction of oxygen.

The satisfactory agreement between the calculated and the experimental values of K' suggests that the physical model upon which the theoretical analysis is based represents a useful approximation for predicting the burning rates of single drops of the fuels considered.

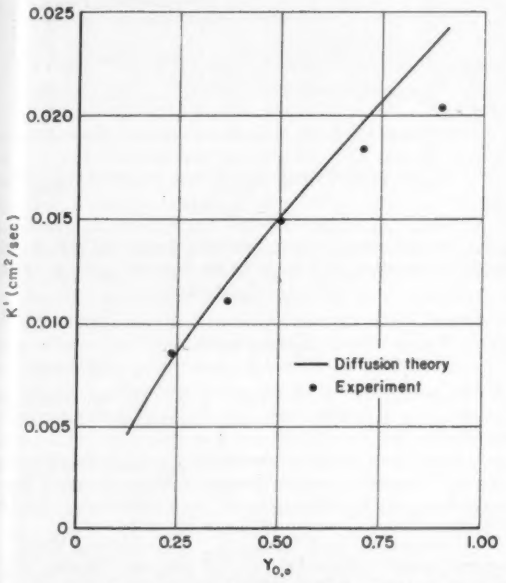

Fig. 7 Comparison of experimental and theoretical values for the evaporation constant (K') for ethyl alcohol burning in various oxygen-nitrogen mixtures

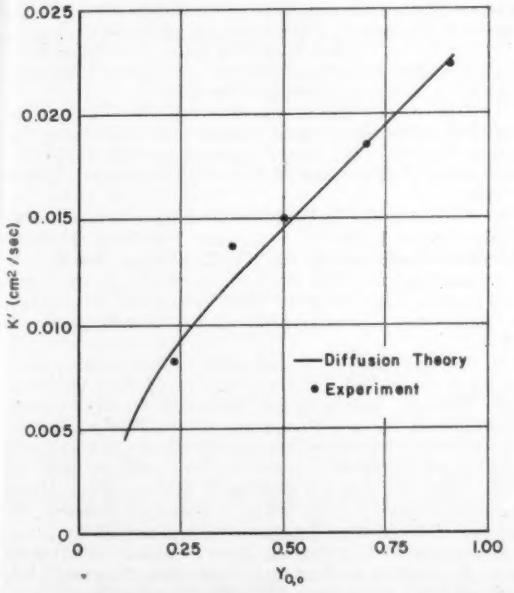

Fig. 8 Comparison of experimental and theoretical values for the evaporation constant (K') for n-heptane burning in various oxygen-nitrogen mixtures

B The Influence of Pressure on Droplet Burning Rate

According to the diffusion theory of droplet combustion, little change in burning rate is to be expected as the pressure in the surrounding atmosphere is increased. The only influence of pressure on the final expression for the evaporation constant is due to the change in normal boiling point, density, and latent heat of vaporization of the liquid fuel. These effects are small and do not account for the comparatively larger changes observed experimentally by Hall and Diederichsen (7) and in the present investigation.

Several explanations might be offered for this discrepancy. Chemical reaction rates are sensitive functions of the pressure (for a complicated process, an over-all dependence for the reaction rate on the square of the pressure is not unreasonable) and, therefore, a very weak dependence of burning rate on reaction rates could account for the observed variation. Furthermore, the effects of radiant heat transfer to the liquid fuel, which were neglected in the diffusion theory, increase rapidly with pressure and could account for a weak dependence of burning rate on ambient pressure.

It has been proposed that the inevitable convection currents may lead to a slight variation in burning rate with pressure. It has been pointed out by Lorell and Wise (11) that some conventional heat transfer correlations indicate that the heat transfer coefficient for a sphere under conditions of free convection is proportional to the one-half power of the pressure. They suggest, by analogy, that it is the influence of pressure on the free convection currents surrounding the burning droplet that accounts for the observed variation in burning rate. However, the experiments on forced convection indicate that only a small increase in burning rate is to be expected as the flow velocity resulting from free convection is increased (owing to the increased pressure), as the free convection velocity is a few centimeters per second. Therefore, this explanation for the increase in burning rate is open to considerable doubt.

C The Influence of Increased Ambient Temperature on Burning Rate

The diffusion theory predicts an increase in burning rate, and hence of K', with increasing ambient temperature. A summary of calculated results for n-heptane and benzene burning in air at elevated temperatures is presented in Table 6.

Table 6 Calculated values for the burning of drops of n-heptane and benzene at elevated temperatures according to the diffusion theory

T_0(°K)	T_c(°K)	r_c/r_l	K' (cm²/sec)
	n-Heptane		
300	3230	8.6	0.0086
410	3300	8.3	0.0090
800	3600	7.7	0.0096
1025	3780	7.3	0.0101
	Benzene		
300	3450	9.6	0.0100
425	3510	9.5	0.0101
700	3730	8.5	0.0104
1025	3990	8.4	0.0112

As has been noted, considerable scatter exists in the data of Kobayasi (9) for burning measurements made at high temperatures. Some doubt exists also as to the validity of the data taken at lower temperatures in the course of the present investigation. However, both sets of data are presented in Figs. 9 and 10, together with the predictions of the theory. Only fair agreement is noted, in contrast to the excellent

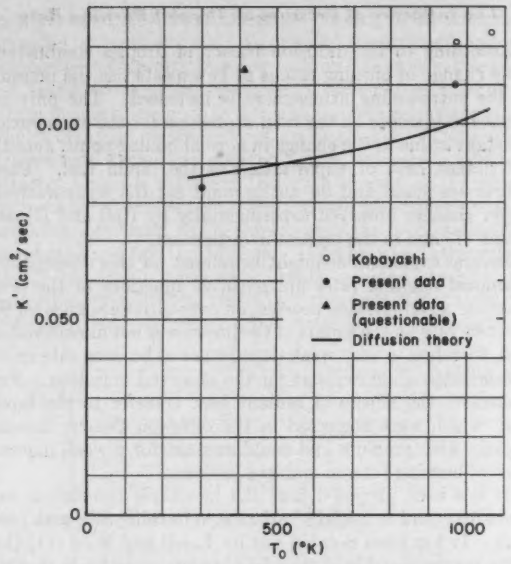

Fig. 9 Comparison of experimental and theoretical values of the evaporation constant (K') for n-heptane burning in air at various ambient temperatures

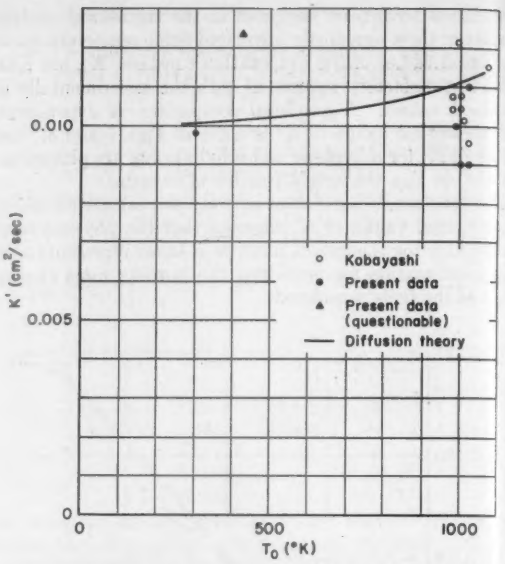

Fig. 10 Comparison of experimental and theoretical values of the evaporation constant (K') for benzene burning in air at various ambient temperatures

agreement obtained for the variation of K' with gas composition.

Since the diffusion theory makes no allowance for the mass or heat transport by natural or forced convection, it is not possible to compare the observed dependence of K' on flow velocity with theoretical predictions.

Conclusions

The comparisons between theory and experiment made in the preceding paragraphs suggest that the physical model upon which the diffusion theory is based represents a useful approximation for the fuel-oxidizer systems considered. However, there are serious doubts that the basic physical assumptions involved in the theoretical model are applicable to certain chemical systems, where the rates of chemical reaction are slow or extensive decomposition of the fuels may occur without the presence of oxidizer. For example, in a recent investigation (12) it was found that the theory satisfactorily predicted the burning behavior of nitromethane in air, but was inadequate to explain the observed burning rate of hydrazine in air.

In the spite of the apparent deficiencies in the state of knowledge concerning the burning behavior of isolated, single drops, it appears that the most important subject for future research in this field is the relation of single droplet burning to fuel spray combustion behavior. An attempt has been made recently by Graves (13) to correlate known droplet burning rates with observed turbojet combustor performance. The variation of experimentally observed burning rates of isooctane droplets in various oxygen-nitrogen mixtures was used to try to predict the change in combustion efficiency of a turbojet combustion can as the initial conditions of the inlet gas were varied. The predicted increase in combustion efficiency as the inlet oxygen concentration was raised fell short of the increased combustion efficiency observed in actual combustion chamber tests. This result suggests that the relation of single droplet burning to spray combustion must be carefully investigated before the results of research on single droplets can be considered useful for the over-all spray combustion problem.

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Interference Effects During Burning in Air for Stationary n-Heptane, Ethyl Alcohol, and Methyl Alcohol Droplets[1]

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Experiments have been conducted for the determination of the evaporation constant and flame shapes of two and of five closely spaced droplets burning in air. Droplets of approximately the same and of different diameters were used at various distances between the droplet centers. The apparent flame shape, which was observed only for n-heptane droplets, changes very little during burning. The square of the droplet diameter decreases linearly with time for fixed spacing between droplet centers, at least within the experimental limits of accuracy. In general, the average evaporation constant for two droplets, $\bar{K}'$, must be assumed either to vary continuously during burning or else to be a function of average initial drop diameter, $\bar{D}^0$. The change of $\bar{K}'$ with time corresponds to the second derivative in plots of the square of the diameter vs. time. These second derivatives are not defined in our work because of unavoidable scatter of the experimental data. Attempts at understanding the observed results by considering published theories for single droplets, as well as groupings obtained from dimensional analysis, have been unsuccessful. It appears that the diffusion model for the heterogeneous burning of single fuel droplets will require serious revision and extension before the burning of droplets arrays and sprays can be understood quantitatively. Furthermore, the effective value of K' for a spray probably depends not only on the fuel-oxidizer system but also on the injection pattern. For this reason additional studies had best be carried out under conditions corresponding to those existing in service models.

Nomenclature

a	=	vertical distance from center of droplet to lower flame surface
b	=	horizontal distance from center of droplet to outside flame surface
C^0	=	initial minimum distance between adjacent droplet surfaces
C	=	minimum distance between adjacent droplet surfaces at time t
D^0	=	initial droplet diameter
D	=	droplet diameter at time t
K'	=	evaporation constant
K''	=	evaporation frequency
$\bar{D}^0$	=	arithmetic average value of D^0 for droplets 1 and 2
$\bar{D}$	=	arithmetic average value of D for droplets 1 and 2
$\bar{K}'$	=	arithmetic average value of K' for droplets 1 and 2
$\bar{K}''$	=	arithmetic average value of K'' for droplets 1 and 2
$\bar{D}'$	=	size constant in Rosin-Rammler distribution law
n	=	distribution constant in Rosin-Rammler distribution law
w	=	weight fraction of the spray composed of droplets with diameter larger than D
$\dot{m}_F$	=	mass burning rate of fuel droplet
ν	=	stoichiometric ratio of mass of O_2 burnt for unit mass of fuel burnt
p	=	pressure
Δl	=	specific latent heat of evaporation of fuel
q	=	standard specific enthalpy difference between reactants and reaction products
c_p	=	specific heat at constant pressure
ρ	=	density
T	=	temperature
T_c	=	temperature of the reaction surface
λ	=	thermal conductivity
η	=	viscosity coefficient
D_F, D_O	=	diffusion coefficients
Sc	=	Schmidt number for the fuel $= \eta_F/\rho_F D_F$
Pr	=	Prandtl number for the fuel $= \eta_F c_{p,F}/\lambda_F$
R_A	=	gas constant per gram of air
Gr	=	Grashof number
g	=	gravitational acceleration
β'	=	coefficient of expansion of air

Subscripts

1	=	the larger of two droplets
2	=	the smaller of two droplets
l	=	liquid droplet
P	=	reaction product
F	=	gaseous fuel
O	=	oxygen
A	=	air

I Introduction

A CONSIDERABLE number of theoretical and experimental papers has been published on the burning of single droplets of fuel (1–5).[5] Experimental studies have been performed on single droplets suspended from fine quartz fibers and burning in an oxidizing atomosphere (5). An approximate theoretical prediction of mass burning rate for single droplets can be obtained on the assumption that mass transport by diffusion to the flame surface and heat conduction to the burning droplet control the burning rate (4).

Recently an attempt has been made by Graves and Gerstein to utilize experimental data for single droplets in the description of burning rates in sprays (6). These authors started with the results of an important theoretical study carried out some years ago by Probert (7). Probert made the following assumptions:

(a) The spray particle size follows the Rosin-Rammler distribution law

$$w = e^{(-D/\bar{D}')^n} \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

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[4] Associate Professor of Jet Propulsion. Mem. ARS.

[5] Numbers in parentheses indicate References at end of paper.

where w equals the volume fraction or weight fraction of the spray composed of drops with diameters greater than D, $\bar{D}'$ is called the size constant, and n is usually referred to as the distribution constant.

(b) The rate of burning of the droplets is taken to be proportional to the first power of the droplet diameter. In this case it is easily shown that

$$D^2 = (D^0)^2 - K't \ldots \ldots \ldots \ldots \ldots \ldots [2]$$

where D is the droplet diameter at any time, D^0 is the initial diameter, and K', which has the dimensions of area per unit time, is known as the evaporation constant.

Probert has shown how to compute the percentage of unburned fuel as a function of $\sqrt{K't_r}/\bar{D}'$ for values of n between 2 and 4, where t_r is the residence time of the burning droplets. Recently correlations similar to those of Probert have been worked out for droplet distribution laws other than the Rosin-Rammler distribution law (8).

Equation [2], which determines droplet diameter as a function of time, is known to correlate all of the observed results for the steady burning of single fuel droplets in an oxidizing atmosphere (4). Therefore, it is of obvious interest to determine whether or not the value of the evaporation constant, K', for single droplet theory or experiment has any relation to the value of K' appropriate for spray combustion. Graves and Gerstein attempted to answer this question by measuring the combustion efficiency as a function of oxygen concentration for a single tubular combustor using isooctane as fuel and countercurrent injection. They compared observed combustion efficiencies with calculated combustion efficiencies using Probert's theoretical analysis in conjunction with values of K' measured for the burning of single droplets. This comparison showed that all of the observed results could not be explained unless spray combustion involves effects, at least for oxygen concentrations below 24 per cent, which can be ignored in the burning of single droplets. In connection with the use of single droplet data for studies on spray combustion, it is therefore of obvious importance to carry out laboratory studies on interference between droplets during burning.

Although, as a general rule, statistical arrays are more easily interpreted than small numbers of droplets, such as 2, 5, etc., experimental studies on small numbers of droplets may provide a clue for the important physico-chemical processes operative in droplet interference during burning. For this reason experiments have been carried out on the variation of K' with droplet size and droplet spacing for two and five closely spaced droplets.

We present in Section II a summary of experimental results obtained for n-heptane, ethyl alcohol, and methyl alcohol droplets. Attempts at finding simple correlations for the experimentally determined evaporation constants are outlined in Section III. Section IV contains some qualitative considerations relating to flame shapes for the burning of single stationary fuel droplets in air. Attempts at clarifying the observed data on the basis of results obtained from dimensional analysis form the subject of Section V.

II Experimental Studies on the Burning in Air of Two Stationary Fuel Droplets

A Apparatus

In order to record the flame shape and the decrease in droplet diameter with time, the droplets were suspended on thin quartz fibers which were secured by means of Sauereisen cement to a metal rod. The rod was bent at an angle of 90 degrees and was supported on a stand by means of a clamp. Rods of various diameters were used for different minimum spacings between the adjacent surfaces of the droplets, C^0 (see Fig. 1). The fibers were either enclosed in a circular plastic tube of several inches diameter or else were burnt in the open air; no significant differences between the burning rates were found in the two cases. Single droplets of fuel were suspended from the fibers by forcing fuel through a hypodermic needle onto the fiber. The droplets were reasonably spherical as shown, for example, in the photograph of Fig. 2. The drops were ignited by using either an automobile ignition system, connected to electrodes which straddled the two quartz fibers through holes in the tube (see Fig. 3), or else simply by using a match.

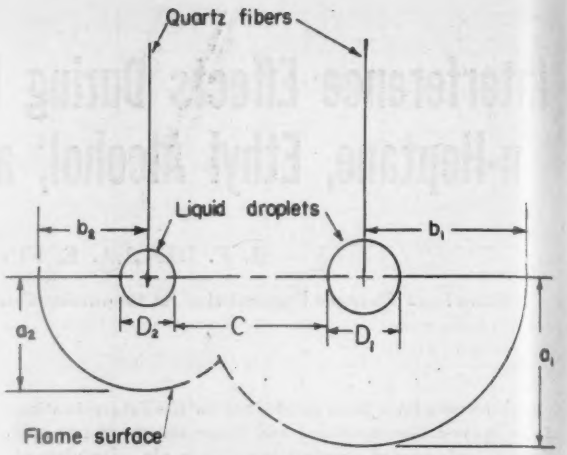

Fig. 1 Schematic arrangement of flame interference experiment with two droplets burning in close proximity

An electrically driven Arriflex 35-mm movie camera was used for photographing the burning droplets. A 100-watt bulb was placed behind the burning drops. Both a silhouette of the drops and the flame front were visible. A 10-inch adapter tube and telephoto lens were employed in order to obtain as large an image as possible on each frame of film. Kodak Plus X and Kodak Supper XX films were used with apertures of f3.2 to f9.

A stroboscope served as timing standard. A 10-inch circular aluminum plate, with three holes placed 120 degrees apart, was secured to a 75 rpm constant-speed motor giving 3.75 flashes per second. The stroboscope was placed directly behind the burning drops. The camera speed was adjusted to about 25 frames per second.

A $^3/_{32}$-inch ball bearing was photographed at the beginning of each 100-ft roll of film used. The image served for calibration and was obtained under the same focusing conditions as were used for the burning droplets.

The film was measured by using a microfilm recorder and a steel scale graduated in millimeters. Two measurements were made on each drop, namely, the two perpendicular diameters inclined 45 degrees to the major and minor axes in the plane of observation. The mean value of these two readings was recorded as the "effective diameter" of the droplet. It is easily shown that, if the major and minor axes do not differ greatly, as was the case in our experiments, then the volume of a sphere with the measured effective diameter is not greatly different from that of the prolate spheroid, which actually corresponds to the shape of our droplets. In most cases measurements were taken from ignition to burn-out and recorded approximately every fifth or sixth frame. The flame shape parameters a_1, a_2, b_1, and b_2(see Fig. 1) were also measured for n-heptane droplets.

B Experimental Results Relating to Flame Shape and Burning Rate

Experimental studies have been carried out for two stationary n-heptane, ethyl alcohol, and methyl alcohol droplets burning in air. The square of the droplet diameter, D^2, was

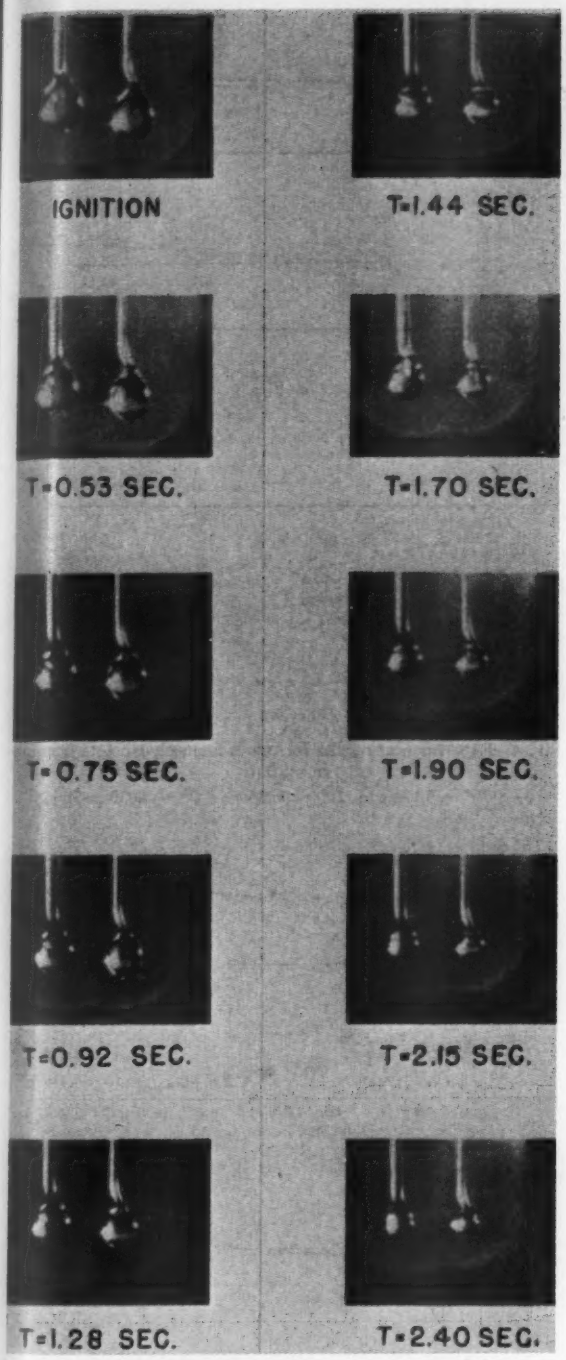

Fig. 2 Photograph of two n-heptane droplets burning in air ($D_1^0 = 0.181$ cm; $D_2^0 = 0.174$ cm; $C^0 = 0.114$ cm)

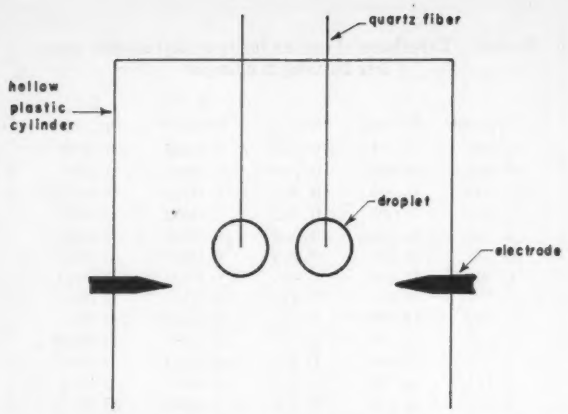

Fig. 3 Schematic diagram of apparatus used for droplet ignition

Table 1 Experimental results for two n-heptane droplets burning in still air

D_1^0, cm	D_2^0, cm	C^0, cm	K_1', cm²/sec	K_2', cm²/sec
0.194	0.166	0.020	0.0094	0.0082
0.181	0.174	0.114	0.0096	0.0094
0.166	0.154	0.183	0.0135	0.0130
0.192	0.176	0.230	0.0105	0.0096
0.165	0.142	0.264	0.0136	0.0122
0.182	0.173	0.752	0.0153	0.0141
0.182	0.182	0.892	0.0140	0.0140
0.173	0.173	1.125	0.0139	0.0133
0.182	0.156	1.47	0.0124	0.0115
0.130	0.127	0.222	0.0080	0.0072
0.138	0.134	0.208	0.0068	0.0063
0.135	0.117	0.313	0.0085	0.0085
0.124	0.124	0.235	0.0070	0.0070
0.133	0.122	0.540	0.0091	0.0090
0.136	0.120	0.496	0.0091	0.0068
0.121	0.118	0.384	0.0074	0.0074
0.143	0.142	0.533	0.0118	0.0110
0.141	0.135	0.538	0.0097	0.0093
0.155	0.142	0.496	0.0122	0.0114
0.156	0.147	0.813	0.0123	0.0113
0.156	0.141	0.883	0.0110	0.0112
0.156	0.156	1.10	0.0107	0.0108
0.208	0.155	0.120	0.0107	0.0104
0.209	0.170	0.352	0.0123	0.0109
0.198	0.140	0.375	0.0090	0.0089
0.167	0.115	0.520	0.0150	0.0090
0.160	0.131	0.532	0.0140	0.0150
0.192	0.148	0.026	—	0.0068
0.208	0.164	0.150	—	0.0124
0.191	0.178	0.246	0.0157	—
0.192	0.180	0.355	—	—
0.202	0.179	0.362	—	—
0.200	0.15	0.466	0.0133	—

generally found to be a linear function of the time, t, for each of the burning droplets. The flame shape parameters (for n-heptane droplets) varied remarkably little with time as the droplets burned. Representative experimental results are shown in Figs. 4 to 10. The data plotted in Fig. 6 correspond to a case in which a relatively long time elapsed before steady burning occurred.

The experimental data obtained for K' are summarized in Tables 1 to 3 for n-heptane, ethyl alcohol, and methyl alcohol, respectively. The listed values of K' were obtained by drawing "best" straight lines through the experimentally determined points except for those cases in which the data were not adequately represented by linear correlations. In some cases the measured results suggested periodic variations of observed parameters.

In several instances, where droplets of greatly different sizes were used, observations were possible on the larger remaining droplet after the smaller droplet had burned out. In most of these cases the slope of the D^2 vs. t curve changed rather abruptly for n-heptane droplets and yielded data in fair agreement with the known single droplet results ($K' \simeq 0.008$ cm²/sec) after the smaller droplet had burned completely. For droplets of nearly equal diameters ($D_1^0 \simeq D_2^0$) the evaporation constants K_1' and K_2' were found to be nearly equal.

Table 2 Experimental results for two ethyl alcohol droplets burning in open air

D_1^0, cm	D_2^0, cm	C^0, cm	K_1', cm²/sec	K_2', cm²/sec
0.097	0.091	0.044	0.0067	0.0053
0.100	0.089	0.199	0.0065	0.0065
0.100	0.095	0.438	0.0075	0.0070
0.102	0.097	0.032	0.0052	0.0052
0.104	0.104	0.435	0.0061	0.0063
0.105	0.103	0.298	0.0067	0.0067
0.108	0.102	0.099	0.0063	0.0063
0.111	0.104	0.435	0.0057	0.0053
0.109	0.108	0.773	0.0065	0.0057
0.111	0.109	0.175	0.0073	0.0069
0.111	0.108	0.438	0.0074	0.0082
0.111	0.108	0.295	0.0070	0.0067
0.123	0.111	0.166	0.0068	0.0069
0.123	0.117	0.420	0.0061	0.0066
0.138	0.136	0.184	0.0073	0.0073
0.139	0.137	0.733	0.0073	0.0074
0.143	0.135	0.132	0.0066	0.0076
0.154	0.150	0.175	0.0067	0.0061
0.156	0.149	0.653	0.0074	0.0077
0.157	0.150	0.152	0.0060	0.0059
0.160	0.154	0.181	0.0070	0.0070
0.169	0.169	0.126	0.0070	0.0066
0.172	0.171	0.132	0.0080	0.0080
0.172	0.172	0.640	0.0091	0.0091
0.174	0.169	1.010	0.0076	0.0089
0.176	0.172	0.067	0.0064	0.0066
0.177	0.172	0.184	0.0083	0.0086
0.191	0.187	0.175	0.0081	0.0077
0.190	0.188	0.333	0.0074	0.0081
0.193	0.186	0.105	0.0071	0.0069
0.193	0.187	0.181	0.0080	0.0078
0.194	0.193	0.990	0.0084	0.0087
0.199	0.193	0.175	0.0083	0.0083
0.200	0.196	0.496	0.0085	0.0085
0.201	0.201	0.296	0.0079	0.0084
0.207	0.204	0.184	0.0076	0.0076

Table 3 Experimental results for two methyl alcohol droplets burning in open air

D_1^0, cm	D_2^0, cm	C^0, cm	K_1', cm²/sec	K_2', cm/sec
0.149	0.137	0.120	0.0087	0.0078
0.146	0.145	0.128	0.0080	0.0080
0.149	0.148	0.023	0.0077	0.0077
0.149	0.146	0.426	0.0080	0.0076
0.145	0.137	0.642	0.0071	0.0073
0.140	0.136	0.044	0.0065	0.0065
0.180	0.168	0.117	—	0.0077
0.174	0.162	0.426	0.0083	0.0083
0.186	0.169	0.429	0.0084	0.0089
0.160	0.153	0.699	0.0070	0.0076
0.204	0.202	0.061	0.0082	0.0080
0.193	0.189	0.511	0.0093	0.0087
0.212	0.200	0.435	0.0082	0.0085

III Correlations for Evaporation Constants

If the evaporation constant, K', of a stationary fuel droplet suspended from a quartz fiber is modified extensively by the presence of a second droplet burning in close proximity, then one might expect the value of K' to depend both on the instantaneous values of the droplet diameters and on the distance between the droplets. Contrary to this idea, it has been found that K' is constant, within the experimental limits of accuracy, for two droplets burning in close proximity.

The observed values of $\bar{K}' = (1/2)(K_1' + K_2')$, for droplets in which D_1^0 and D_2^0 did not differ by more than 20 per cent,

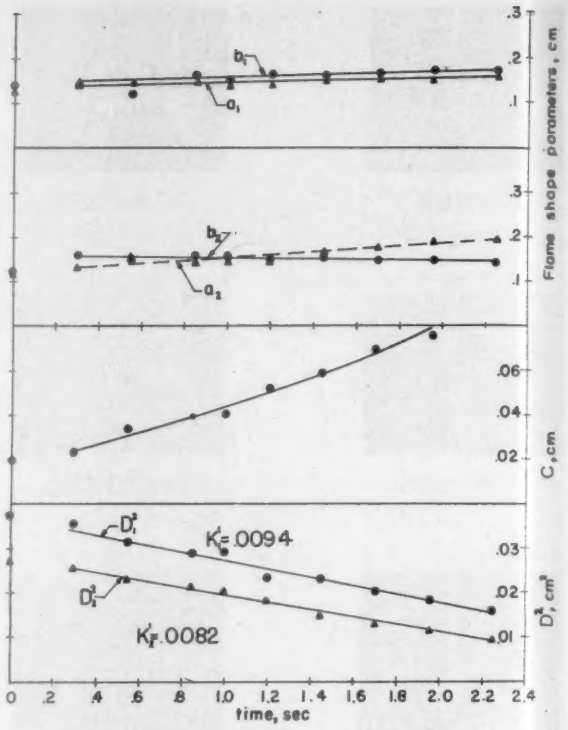

Fig. 4 Experimental results for two n-heptane droplets burning in still air

(D_1^0 = 0.194 cm; D_2^0 = 0.166 cm; C^0 = 0.020 cm)

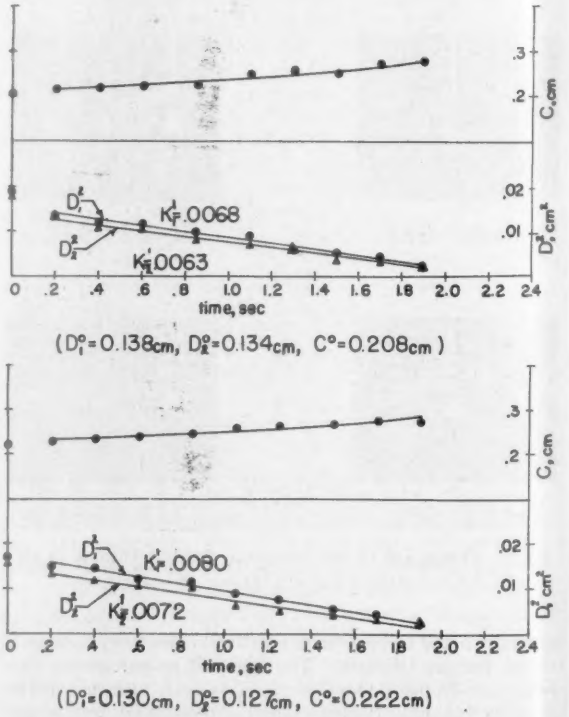

Fig. 5 Plots of D^2 vs. time and C vs. time for two n-heptane droplets burning in still air

are plotted as a function of C^0 in Figs. 11 to 13 for n-heptane, ethyl alcohol, and methyl alcohol, respectively.

Reference to Fig. 11 shows that the experimental results fall roughly into two categories depending on the initial average

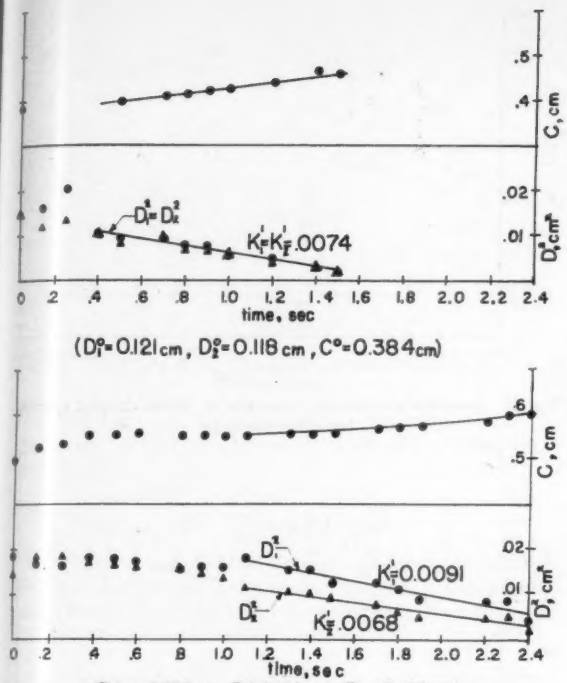

Fig. 6 Plots of D^2 vs. time and C vs. time for two n-heptane droplets burning in still air for various C^0

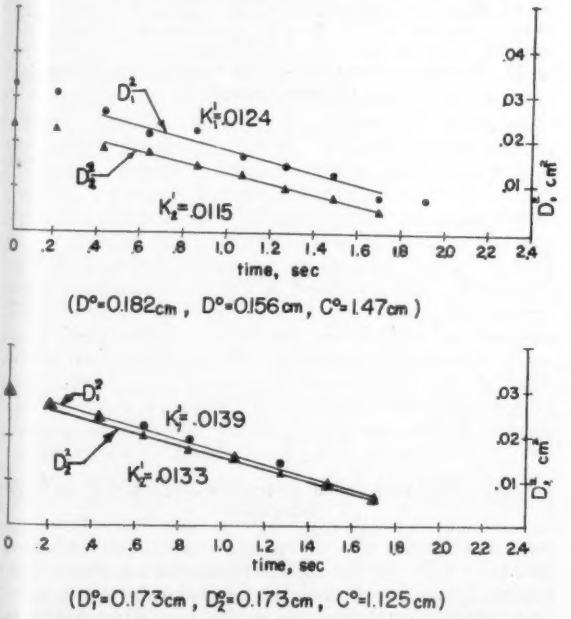

Fig. 7 Plots of D^2 vs. time for two n-heptane droplets burning in still air

droplet diameter $\bar{D}^0 = (1/2)(D_1^0 + D_2^0)$. The average evaporation constant increases when C^0 is reduced from larger values with negligible droplet interference, presumably because heat losses from the flame surface are reduced by the proximity of a second heat source for sufficiently small values of C^0; $\bar{K}'$ reaches a maximum and then decreases again as C^0 is made still smaller. A decrease in $\bar{K}'$ for very small values of C^0 could be produced through the creation of oxygen-deficient atmospheres resulting from increased competition for the oxygen supply furnished by convection and diffusion. On the basis of the proposed picture, the maximum in plots of $\bar{K}'$ vs. C^0 results through a balance between two

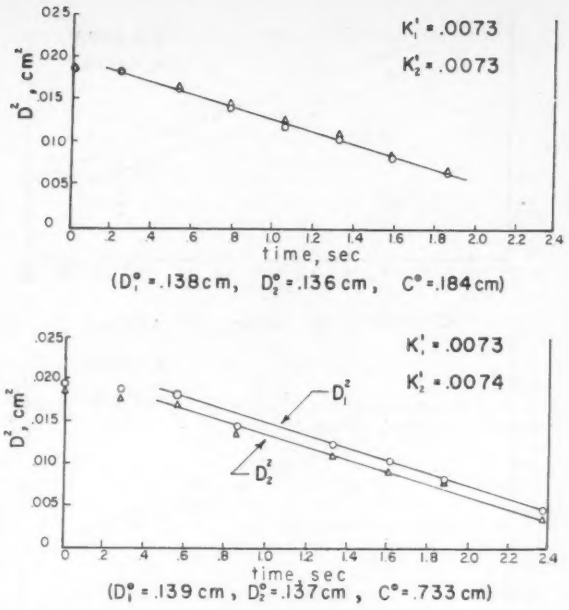

Fig. 8 Plots of D^2 vs. time for two ethyl alcohol droplets burning in still air

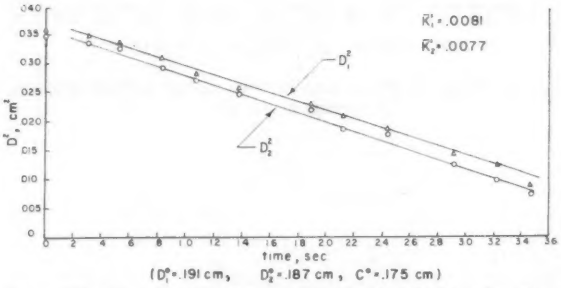

Fig. 9 Plot of D^2 vs. time for two ethyl alcohol droplets burning in still air

opposing factors, viz., decreased heat loss and decreased oxygen supply. The proposed interpretation, if applicable to spray combustion, may be of considerable practical importance.

The experimental data for n-heptane droplets plotted in Fig. 11 suggest a strong dependence of $\bar{K}'$ on $\bar{D}^0$ unless $\bar{K}'$ is not really constant and varies continuously during burning. In this connection it should be emphasized that changes of $\bar{K}'$ with time correspond to changes of the second derivative in plots of D^2 vs. t. These second derivatives, in turn, are not defined in our studies because of unavoidable scatter of the experimental data.

The observed values of $\bar{K}' = (1/2)(K_1' + K_2')$ for ethyl and methyl alcohol droplets as a function of C^0 (see Figs. 12 and 13, respectively) do not permit any simple grouping into "small" and large droplets. It appears, furthermore, that $\bar{K}'$ is a somewhat weaker function of $\bar{D}^0$ for the two alcohols than for n-heptane.

A Correlations for n-Heptane Droplets

A number of attempts were made to relate $\bar{K}'$ with simple functions of C^0, $C^0/\bar{D}^0$, $C^0 + \bar{D}^0$, $(C^0 + \bar{D}^0)/D^0$, etc., in order to reduce the scatter of experimental points for different values of $\bar{D}^0$. These efforts were, however, unsuccessful and suggest that the evaporation constant $\bar{K}'$, which is independent of initial droplet diameter in single droplet studies, loses its significance as a basic correlating parameter for two n-heptane droplets burning in close proximity. Whether or not this conclusion applies to sprays cannot be said without further experimental work. The fact that $\bar{K}'$ appears to vary with $\bar{D}^0$ is shown more directly by plotting $\bar{K}'$ as a func-

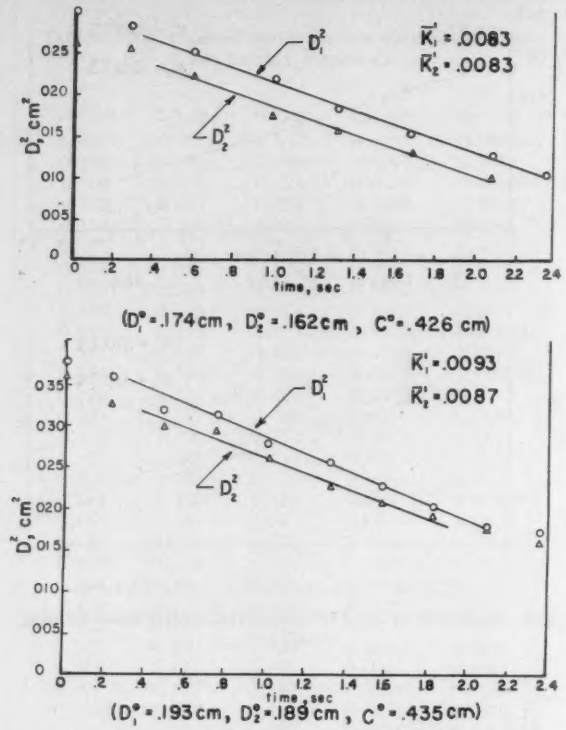

Fig. 10 Plots of D^2 vs. time for two methyl alcohol droplets burning in still air

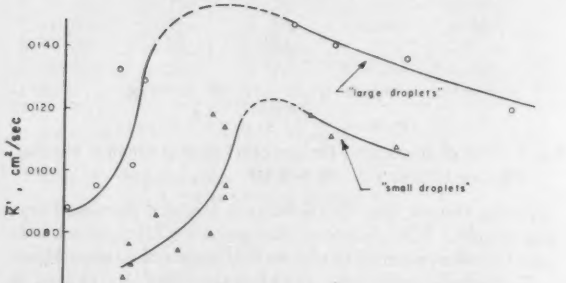

Fig. 11 Variation of the average evaporation constant with C^0 for n-heptane droplets with different initial average diameters $\bar{D}^0$

tion of $\bar{D}^0$ for a group of experimental data with nearly equal values of $C^0 + \bar{D}^0$.

Two burning droplets meet the requirements of geometric similarity when they have the same values of $C/\bar{D}$ and of $\bar{D}$. It is easily shown from plots of $C/\bar{D}$ vs. $\bar{D}$ that (nearly) intersecting curves are characterized by greatly different values of $\bar{K}'$ if the values of $\bar{D}^0$ are different. In other words, if $\bar{K}'$ is really constant during burning, then the value of the evaporation constant is determined primarily by the initial conditions and only to a lesser extent by geometrical arrangement.

In view of the apparent dependence of $\bar{K}'$ on $\bar{D}^0$, attempts were made to find a simple function of $\bar{K}'$ and $\bar{D}^0$ which would depend only on C^0 or on a known function of C^0 and $\bar{D}^0$. An obvious choice is the ratio $\bar{K}'' = \bar{K}'/(\bar{D}^0)^2$ to which we shall refer as the evaporation frequency.

In Fig. 14 we have plotted $\bar{K}''$ as a function of $C^0/\bar{D}^0$. Reference to Fig. 14 shows that a fair correlation of all of the experimental data has been obtained, the scatter being perhaps smaller in similar plots using C^0 and $C^0 + \bar{D}^0$ as abscissa than in the plot shown which uses the dimensionless quantity $C^0/\bar{D}^0$. In the absence of an adequate theory concerning droplet interference, the significance of the observed "correlations" is obscure, as is also any extrapolation to sprays. For this reason we must content ourselves with the observation that, for two n-heptane droplets burning in close proximity, the observed values of $\bar{K}'/(\bar{D}^0)^2$ are fairly well represented as a function of either $C^0/\bar{D}^0$, C^0 or $C^0 + \bar{D}^0$. Constancy of the evaporation frequency, except for variations in C^0, means that the fundamental burning rate law for fixed values of C^0 has the form

$$(\bar{D})^2 = (\bar{D}^0)^2 - \bar{K}''(\bar{D}^0)^2 t \quad \ldots\ldots\ldots\ldots [3]$$

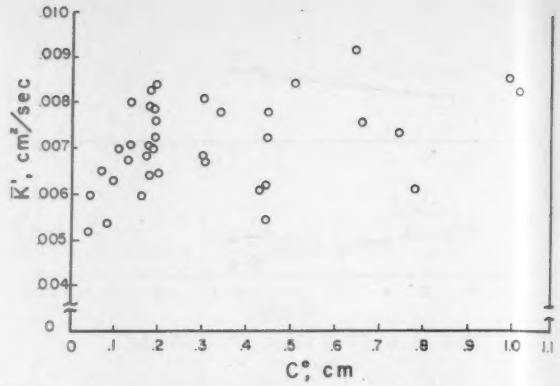

Fig. 12 Average evaporation constant vs. initial droplet spacing for ethyl alcohol

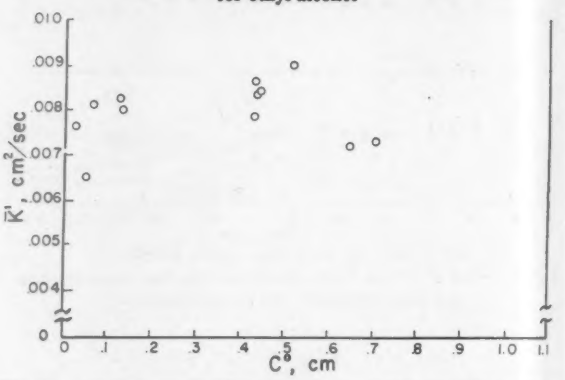

Fig. 13 Average evaporation constant vs. initial droplet spacing for ethyl alcohol

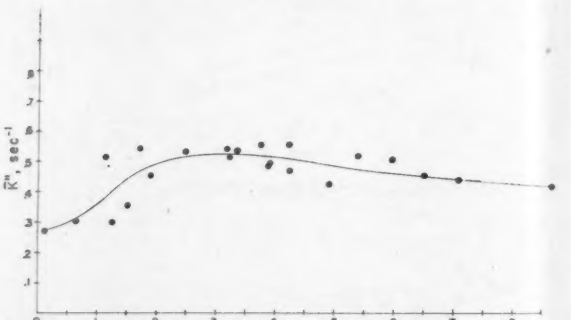

Fig. 14 Dependence of the evaporation frequency $\bar{K}''$ on $C^0/\bar{D}^0$ (n-heptane)

B Correlations for Ethyl and Methyl Alcohol Droplets

No outstandingly successful group for correlating the observed data for $\bar{K}'$ as a function of $\bar{D}^0$, C^0, or $C^0/\bar{D}^0$ was found for the alcohols. The fact that $\bar{K}'$ is sensitive to changes in

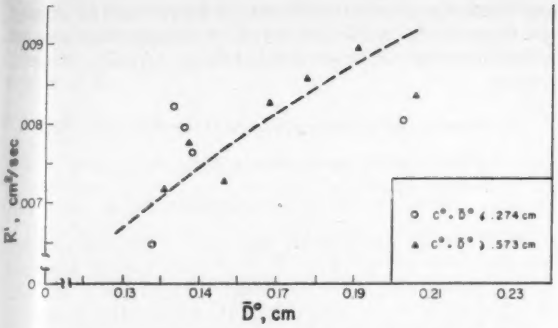

Fig. 15 Variation of $\bar{K}'$ with $\bar{D}^0$ for ranges of values of $C^0 + \bar{D}^0$ (methyl alcohol)

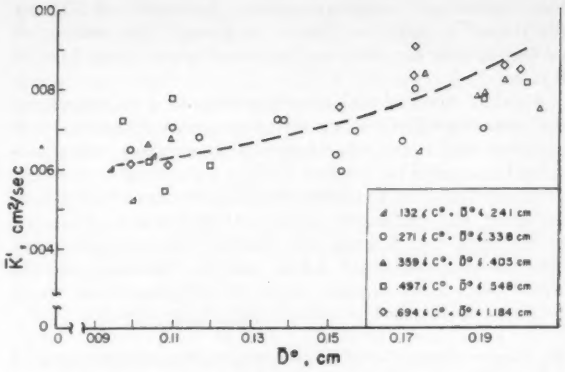

Fig. 16 Variation of $\bar{K}'$ with $\bar{D}^0$ for ranges of values of $C^0 + \bar{D}^0$ (ethyl alcohol)

$\bar{D}^0$ can be seen from Figs. 15 and 16 in which curves are shown connecting the experimental results obtained for similar values of $C^0 + \bar{D}^0$.

IV Flame Shapes

The flame shapes for two droplets, as for single droplets, are determined largely by convection currents. A qualitative description of flame shapes can be given on the basis of available experimental measurements.

A Flame Shapes for Single Stationary Fuel Droplets Burning in Air

According to an elaboration[6] of observations by Kumagai and Kimura (9), a realistic description can be obtained for the flame shape surrounding a burning, single, stationary, droplet of fuel in air by allowing for the influences of free convection.

A burning fuel droplet in air must produce free convection currents. In Fig. 17 we show a schematic diagram of the flame shape for a single droplet. We shall assume that the convection velocity corresponds to a uniform flow with velocity U at some distance upstream from the initial, undisturbed, flame front. The combination of burning droplet and convective flow then acts as a source in a uniform flow field and, at steady burning, establishes the flow pattern corresponding to a half body as lower boundary. The stream surface through the lower stagnation point may be thought of as dividing initially the stream lines originating from the source (fuel droplet) and the stream lines established by convective flow. This situation is, however, unstable, and diffusive transport of oxidizer and fuel across the stream surface must be established. The tangential flow velocities at the stream surface of fuel vapor and air are initially equal. Presumably concentration and temperature gradients are established during steady burning in such a way that diffusive transport of fuel and oxygen brings a stoichiometric mixture roughly to the stream surface, thereby making the lower stream surface a flame surface.

Some of the fuel vapor is deflected around the stream surface and ultimately moves vertically upward through a cylinder of diameter $2b$. An air flow is established parallel to the fuel flow, moving with a velocity which, in first approximation, may be assumed to be uniform and equal to U. Hence conditions are established for the formation of an overventilated diffusion flame and the flame height h can presumably be calculated roughly from the classical treatment of Burke and Schumann for diffusion flames.

The preceding remarks may be summarized by noting that the effect of free convection is, in first approximation, a distortion of the spherical flame front to a flame surface whose

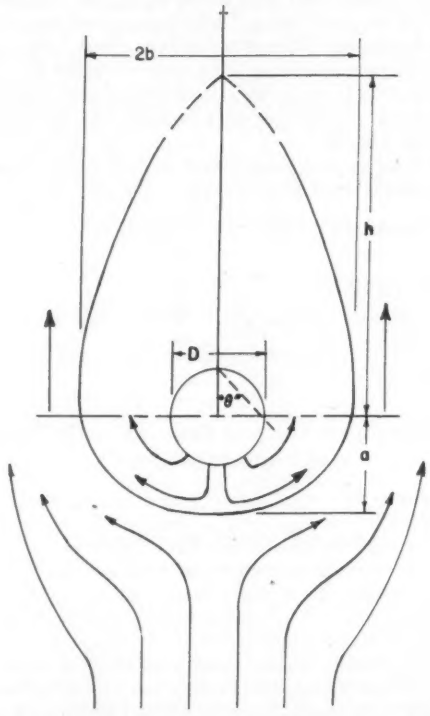

Fig. 17 Schematic diagram of burning fuel droplet. The streamlines are identified by arrows

lower boundary is the stream surface corresponding to a source of strength $\dot{m}_F/\rho_F$ ($\dot{m}_F$ = mass rate of burning of fuel droplet, ρ_F = density of fuel vapor) in a uniform flow of velocity U; the upper flame surface may be described as the flame front for a cylindrical diffusion flame with the inside cylinder of diameter $2b$ and flow velocities of fuel and air equal to U.

The postulated description of the flame surface leads to results which are in accord with the observations of Kumagai and Kimura.

Thus $$2b = \sqrt{2\dot{m}_F/S_F\pi U} \quad [4]$$

and $$2b/a = 2\sqrt{2} \quad [5]$$

Furthermore, since $U \sin\theta$ (i.e., the tangential flow velocity of air at the stream surface) must be equal to the tangential flow velocity of fuel vapor, one would expect that U and $\dot{m}_F$ are proportional to each other. Thus

$$U \sim D \quad [6]$$

since $\dot{m}_F$ is known to be proportional to the diameter of the burning fuel droplet. Also b/a should be a constant for a given

[6] The present discussion is based on ideas formulated by Professor L. Lees and one of us (SSP). We are indebted to Professor Lees for permission to include this material in the present report.

fuel droplet and oxidizing medium; Kumagai and Kimura (9) found b itself to remain unchanged for cetane oil as the droplet diameter was increased from about 0.07 to 0.12 cm.

Although the picture of the formation of a heterogeneous diffusion flame given above seems qualitatively correct, it is apparent that a complete solution of the problem under consideration cannot be obtained without a quantitative analysis of energy transport to the droplet from the flame boundaries. However, the qualitative considerations based on the work of Kumagai and Kimura and sketched above suggest that the following important results will be obtained: (a) $\dot{m}_F$ weakly dependent on flame shape; (b) U proportional to D; (c) h proportional to b^2D; (d) b weakly dependent on D.

B Flame Shapes for Two n-Heptane Droplets Burning in Close Proximity

For two n-heptane droplets burning in close proximity, it has already been noted that a_1, b_1, a_2, and b_2 change very little during droplet burning. Furthermore, reference to the original experimental data shows that the ratio of b to a is not sensibly different from unity and does not seem to depend strongly on C^0. In some cases the distances of the flame surfaces from the droplet surfaces remained constant during burning (see Fig. 2).

The droplet spacing parameter C is, of course, determined through the geometric arrangement. Thus

$$C = C^0 + (1/2)(D_1^0 - D_1) + (1/2)(D_2^0 - D_2)$$

or

$$C = C^0 + (1/2)D_1^0(1 - \sqrt{K_1't/(D_1^0)^2}) + (1/2)D_2^0(1 - \sqrt{K_2't/(D_2^0)^2}) \quad \ldots\ldots [7]$$

Needless to say, the time dependence of C is well represented by Equation [7].

V Dimensional Analysis Relating to the Burning of Liquid Droplets

Since the experimental data obtained in the present investigations are not intelligible on the basis of existing theoretical studies for the burning of single fuel droplets (4), it is of interest to re-examine the problem at least qualitatively in an effort to understand the dimensionless groups which govern droplet burning. We take the detailed theoretical studies for single droplets as a guide in this work. In view of the observed importance of chemical effects, which is emphasized by the differences between the alcohols and n-heptane, we cannot expect a complete answer without introducing explicitly dimensionless groups depending on chemical reaction rates. We note, however, that existing theoretical studies must be deficient since, for example, no really satisfactory explanation exists for the variation of burning rate with pressure.

A The Burning of Single Droplets

The burning of a single stationary fuel droplet in an oxidizing atmosphere involves the following 23 variables: Mass burning rate of fuel droplet $\dot{m}_F$; stoichiometric ratio of mass of O_2 burnt for unit mass of fuel burnt, ν; constant pressure p; specific latent heat of evaporation of fuel droplet Δl; standard specific enthalpy difference between reactants and reaction products q; droplet diameter D; specific heats at constant pressure $C_{p,l}$, $C_{p,P}$, $C_{p,F}$ and $C_{p,O}$; densities ρ_l, ρ_f, and ρ_A; temperatures T_l, T_c, and $T_O = T_A$; thermal conductivities λ_F and λ_A; viscosity coefficients η_F, η_O, and η_A; diffusion coefficients D_F and D_O. Here the subscripts l, P, F, O, and A identify liquid fuel, combustion products, gaseous fuel, oxygen, and air, respectively. The temperature T_c is the temperature at the reaction surface. In our physical model the system is characterized by average diffusion, viscosity, and thermal conduction coefficients on the fuel and air sides of the flame front. A suitable set of 18 dimensionless groups[7] is the following: Schmidt number $Sc = \eta_F/\rho_F D_F$, Prandtl number

$$Pr = \eta_F c_{p,F}/\lambda_F,\ \rho_l/\rho_F,\ \rho_A/\rho_F,\ c_{p,F}(T_C - T_l)/\Delta l,\ D_O/D_F,$$

$$\lambda_O/\lambda_F,\ \eta_O/\eta_F,\ \eta_A/\eta_F,\ c_{p,O}/c_{p,F},\ c_{p,P}/c_{p,F},\ c_{p,l}/c_{p,F},\ \nu,$$

$$q/\Delta l,\ (T_c - T_O)/(T_c - T_l),\ p_A/\rho_A R_A T_O$$

where R_A is the gas constant per gram of air, the Grashof number[8] $Gr = D^3\rho^2 g\beta'(T_c - T_O)/\eta_A^2$ where g is the acceleration of gravity and β' the coefficient of expansion of air, and K'/D_F with $K' = -d(D^2)/dt$ as the evaporation constant.

From the conservation of mass equations it is apparent that

$$\dot{m}_F = -\frac{d}{dt}\left(\frac{\pi}{6}D^3\rho_l\right) = \frac{\pi}{4}\rho_l D K'$$

whence

$$K'/D_F = 4\dot{m}_F/\pi\rho_l D D_F \quad \ldots\ldots [8]$$

From the analytic solution (4) for $\dot{m}_F$ (using constant average values for specific heats and thermal conductivities) it is easily shown that

$$\frac{K'}{D_F} = \frac{8(Sc)}{(Pr)}\left(\frac{\rho_F}{\rho_l}\right)\frac{\ln[1 + c_{p,F}(T_c - T_l)/\Delta l]}{[1 - (r_l/r_c)]} \quad \ldots\ldots [9]$$

where r_l/r_c represents the ratio of the radius of the fuel droplet to the radius of the flame surface. The ratio r_l/r_c is a complicated function of several of the dimensionless groups listed previously. By utilizing experimental results obtained for the burning of single droplets we are now able to draw some useful qualitative conclusions.

It has been found that K' is constant during burning and is therefore independent of the instantaneous value of D. Reference to the 18 dimensionless groups shows that only Gr, which determines the magnitude of the convection currents, is a function of D. The constancy of K' during burning therefore suggests that the convection currents induced during burning have no important effect on K'. This observation is in agreement with the result that absolute values calculated for K', without considering the influence of convection, are in fair agreement with experimental measurements (4). The functional relation given in Equation [9] also involves the assumption that convection effects may be neglected in first approximation.

Reference to Equation [9] shows that K' is a linear function of $\rho_F D_F$ and of other terms which are pressure independent, except possibly for r_l/r_c. It has been found experimentally (3) that K' varies as $p^{1/4}$. Hence, in terms of the simple picture used in the derivation of Equation [9], it follows that $[1 - (r_l/r_c)]$ must vary as $p^{-1/4}$ in order to account for the observed variation of K' with pressure. In a more general analysis, in which proper allowance is made for radiant heat transfer and which does not involve the assumption that chemical reactions are fast compared with the transport processes, a dependence of K' on pressure may be introduced through the effect of pressure on radiant energy transport or through pressure-sensitive chemical reaction rates. There is an obvious difficulty in attempting to account for the pressure variation of K' through the influence of the Grashof number and free convection currents. Thus, since K' is constant during burning, it must be independent of (droplet or) com-

[7] According to the Buckingham Pi theorem, the number of dimensionless groups usually equals the number of variables minus the number of dimensions. There are five dimensions in the present problem: length, time, mass, temperature, heat.

[8] The Grashof number may well involve the diameter of the combustion surface, $2r_c$, rather than $D = 2r_l$. Since r_c and r_l are related, this change will not affect the following arguments.

bustion surface diameter. But K' is a more sensitive function of this length than of pressure. Therefore, the pressure dependence of K' should probably not be attributed to the influence of Gr.[9]

B Two Droplets Burning in Close Proximity

For two droplets of equal size, whose centers are separated by a distance $C^0 + \bar{D}^0$, we have the additional variable $C^0 + \bar{D}^0$ and the new dimensionless group $D/(C^0 + \bar{D}^0)$, where D is the diameter of the burning droplets. Since it has been found experimentally that K' for each of the two droplets is also independent of the instantaneous value of D, it seems likely that convection effects are again of secondary importance. However, K' may not be a function of $D/(C^0 + \bar{D}^0)$ but rather of the initial drop diameter $\bar{D}^0$ itself (with the exact dependence varying with fuel type). This result is difficult to understand since it suggests that the entire burning process is influenced by the initial configuration unless, of course, K' is not really constant during burning but varies so little that its change with time (i.e., the change of the second derivative in a plot of D^2 vs. time) cannot be detected with certainty. If K' is really constant during burning, then we are dealing again with a fundamental problem similar to that involved in the pressure dependence of K' for single droplets. Questions of this sort are not answered by dimensional studies alone.

C Five Droplets Burning in Close Proximity

Some experimental data have been obtained also for the burning of an array of five ethyl alcohol droplets in air. Four of the droplets were located at the corners of a square and the fifth in the center of the square. The square of the diameter for the droplet surrounded by four other droplets was again found to decrease linearly with time, with the apparent value of K' about 20 per cent larger than for similar studies on two droplets burning in close proximity.[10] The work has not yet progressed to the point where the variables determining the absolute value of K' are properly defined.

Conclusions

The most important results obtained in the present investigations are the following: (a) within the limits of experimental accuracy, the evaporation constant K' is invariant with time for two droplets burning in close proximity and also for the center droplet of a five-droplet array; (b) the absolute value of K' is not determined by chemical composition alone but depends also on droplet arrangement. The first conclusion is of considerable practical interest since it supports the type of phenomenological considerations used by Probert for analyzing spray combustion. In general, it appears unlikely that D^2 will not decrease linearly with time, in good approximation, for arrays and sprays which are more complicated than those considered by us. The second conclusion underlines the doubts expressed in our introduction about the practical value of results derived from studies on single droplets and simple droplet arrays. In fact, if K' is really dependent on injector design, then it would be better to carry out fundamental studies on spray combustion with injector configurations of the type used in service models. An over-all description of combustion rates in terms of parameters such as an average K' for a spray and an average residence time t, for all of the droplets is sufficient for practical purposes. Quantitative predictions of absolute values for K' in sprays must await more detailed understanding of the importance of chemical reaction rates and convection effects than we shall possess for a long time to come.

[9] The effect of pressure on convective heat transfer to burning droplets has been discussed, for example, by Wise, Lorell and Wood (*Fifth Symposium on Combustion*, pp. 139–140, Reinhold Publishing Corporation, New York, N. Y.). Goldsmith and Perkins (5) have found that the mass burning rate of single droplets is a weak function of air velocity in forced convection experiments. Finally, current experimental results suggest that K' varies as a weak power of the pressure with the exponent dependent on fuel type.

[10] Recent preliminary experiments by Lt. J. Kanevsky on nine droplets arranged in a body-centered cubic lattice have again led to the conclusion that, for the center droplet, the square of drop diameter decreases linearly with time.

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Some New Metallurgical Processes

(*Continued from page 156*)

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Technical Notes

Interpretation of Malina-Summerfield Criterion for Optimization of Multistage Rockets

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A STUDY has been made of the problem of optimizing multistage rocket configurations in so far as performance is affected by changes in the number of stages and redistribution of the fuel and structure weight among the stages. The optimization criterion selected was maximum burnout velocity for given take-off weight. Both tandem (series burning), Fig. 1, and lateral (parallel burning), Fig. 2, configurations were investigated.

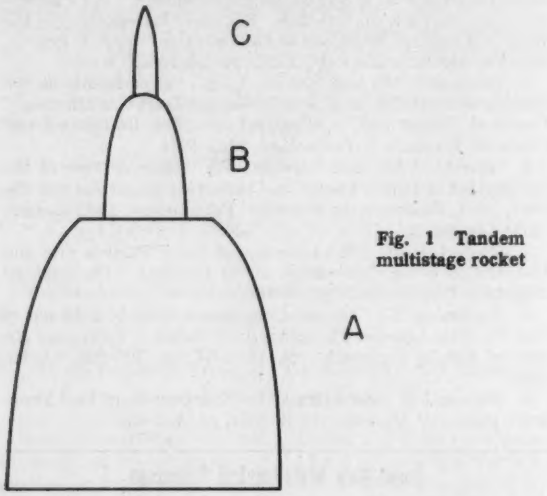

Fig. 1 Tandem multistage rocket

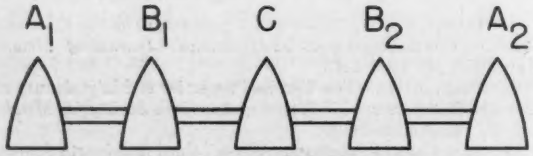

Fig. 2 Lateral multistage rocket

The theory of multistage rockets has been discussed by Malina and Summerfield, whose notation (1)[3] has been used here as far as possible. While they mention only tandem staging explicity, it is important to note that their mathematical reasoning remains valid without change in the case of parallel multistage rockets.

In the case of the tandem rocket, the motor of one stage, A, burns alone until its fuel is exhausted. It is then discarded and, at the same time, the motor of the next stage, B, is ignited. This burns until its fuel is exhausted, and so on.

In the lateral, or parallel, arrangement all rockets burn simultaneously. At the same time, fuel is pumped from the outer to the inner rockets at such a rate that the fuel tanks of all except the outermost units remain full. When the outermost units, A_1 and A_2, are empty, they are discarded. Fuel is then pumped from the next pair of units, B_1 and B_2, inward, and so on. The asymmetric arrangement, consisting only of units A_1, B_1, and C, and in which fuel is pumped from A_1 and B_1 to C, is not emphasized in this note because of its tendency to fly in a curved path and the complexity of the control problem.

The rocket stages are numbered in the order in which they are discarded. In the parallel arrangement, A_1 and A_2, containing motor, fuel, and structure, are the disposable components of the first stage. $M_e^{(n)}$ denotes the (combined) empty mass of the motor(s) of the nth stage, $M_p^{(n)}$ denotes the mass of propellant, $M_i^{(n)}$, which is regarded as the payload mass of the nth stage, is defined to be the combined unburnt mass of the $(n+1)$th and all subsequent stages.

Let v_N be the total velocity of the rocket in the absence of air drag when the last stage ceases to burn, let g_0 be the acceleration of gravity (assumed independent of altitude), t_p the combined burning time of all stages, and c_a the exhaust velocity of the jet with respect to the vehicle. It is assumed that the rocket rises vertically. Malina and Summerfield define the quantity $S = (v_N + g_0 t_p)/c_a$ as a measure of achievement. It will be noted that Sc_a would be the final velocity in the absence of gravity. Let

$$Z_n = \frac{M_e^{(n)} + M_p^{(n)} + M_i^{(n)}}{M_e^{(n)} + M_i^{(n)}}$$

and

$$Z = \prod_{n=1}^{N} Z_n$$

where N is the number of stages. It can be proved that $S = \ln Z$.

Malina and Summerfield assume that $M_e^{(n)}/M_p^{(n)}$ is independent of n. This is a fair approximation in practice. They then state the following theorem:

For given values of S, N, and $M_i^{(N)}$, the total initial mass $M_i^{(0)} = M_e^{(1)} + M_p^{(1)} + M_i^{(1)}$ is a minimum if

$$\frac{M_i^{(n-1)}}{M_i^{(n)}} = \frac{M_e^{(n-1)}}{M_e^{(n)}}$$

independently of n. This theorem applies to parallel configurations as well as to the tandem rockets described in Ref. 1.

It is important that the theorem is valid only for a constant number of stages, N. A rocket with a greater number of stages, but deviating from the Malina-Summerfield rule, may have a larger S than one having fewer stages, but obeying the Malina-Summerfield rule.

Consider a multistage rocket obeying the Malina-Summerfield rule. Let another multistage rocket be designed which has the same payload, structure weight, and propellant weight, but all motors identical with that of the last stage of the Malina-Summerfield rocket. In all cases which have been investigated, it was found that the second (equal stage) case gives the larger S.

A thorough comparison of tandem and parallel configurations is beyond the scope of this note. A selection of one or the other type of staging would depend on the practical considerations related to a specific application. Two important advantages for parallel staging are higher thrust-to-weight ratio and ignition of all motors before launch. Tandem staging, on the other hand, has the advantage of lower acceleration and cleaner design.

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Received Feb. 1, 1956.

[1] Staff Engineer, Armament Section. Mem. ARS.

[2] Engineer, Armament Section.

[3] See Reference at end of paper.

Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, *Associate Editor*
Norman L. Baker, Indiana Technical College, *Contributor*

Jet Aircraft, Engines

DELIVERIES of F-100C Super Sabres are now being made from North American's Columbus, Ohio, Division in addition to the Los Angeles facility. The F-100C is already on operational duty and incorporates inflight refueling provisions, storage space for extra fuel and bombs (including atomic weapons) under its wings, and electronic bombsights. Added fuel capacity allows it to escort bombers or for use as a fighter bomber. Armament is four 20-mm cannons. Specs: span 47 ft; length, 38 ft; height, 15 ft; the Super Sabre can exceed the speed of sound in level or climbing flight.

● A high speed photo-recon plane, the McDonnell RF-101A Voodo, is being delivered to the Air Force. The craft (photo) will enable supersonic photo missions. The RF-101A is powered by two J-57 turbojets which deliver a total of 20,000 lb thrust (without afterburners). Two other models are a fighter version (for Strategic Air Command) and the F-101B for the Air Defense Command.

RF-101A photo-recon Voodoo *McDonnell*

● On a 500 km closed course, the bantam carrier-based atom bomber, Douglas A4D Skyhawk averaged 695.163 mph. The A4D carried a normal load of JP-4 and was powered by one J-65 Sapphire turbojet (without afterburner). The 310.68 mile course at Edwards AFB, Calif., was covered in only 26.8176 min.

● Demon, McDonnell's F3H-2N jet fighter has been qualified for carrier duty in recent Navy tests. Demon is powered by one Allison J-71 turbojet engine of 10,000 lb thrust plus (with afterburner). Speed is on the 600 mph class. Armament consists of rapid firing, high velocity 20-mm cannon plus rockets and externally stored weapons.

● New Canadian all-weather interceptor is the CF-100-4C by Avro. The craft can cruise at a speed of over 600 mph and has a ceiling of over 55,000 ft. Another Avro project is being taken over by the U.S.A.F. This is the so-called "flying saucer" aircraft which is disklike and is powered by a flattened turbojet engine. Canadian investment has been almost $0.5 million to date with an estimate that $100 million would be required to build a flying prototype. The American project is to be carried out by ARDC. At the same time the Air Force announced the taking over of the Avro project, they released a statement about the other so-called "saucer" sightings. They concluded that previous sightings could be explained as natural objects. In addition, the report said that it was improbable that the saucer sightings reflect observations of technical developments outside our present scientific realm, as one would have been led to believe by proponents of "space visitors."

● The F-107A, by North American, is said to feature a variable area intake for optimum thrust delivery. It is designed to operate at Mach 2 and is to get its power from a P&W J-75 turbojet.

707 in civies *Boeing*

● The Boeing 707 jet transport now has logged 319 hr in the air. One test, a nonstop flight from Seattle to Washington, D. C., a distance of 2340 miles, was completed in 3 hr 58 min at an average speed of 592 mph. The 707 has flown at altitudes of over 45,000 ft and at speeds of over 600 mph. The prototype grosses 190,000 lb, while production models will tip the scale at 230,000 lb. Pan American World Airways has purchased 20 of the 707's (photo) for use in its commercial operations during the forthcoming years.

● Two British interceptors—the Avro and the Sanders-Roe—are said to utilize combination rocket-turbojet power plants. Peroxide engines may be used.

● Flight tests of the 600 mph jet seaplane, the XP6M-1 Martin Seamaster have been successful. Powered by four Allison J-71 turbojets with afterburners, its specs include: length, 134 ft; span, 100 ft; height, 31 ft; hull width, 10 ft; payload, 30,000 lb; cruising altitude, 40,000 ft (photo). Designed for mine laying and photo-recon work, the Seamaster has such features as: tall T-shaped tail, wing-tip jet engine nacelles, and fixed plastic wing-tip floats which provide buoyancy while the aircraft is in the water.

Martin

Seamaster in the air. Note overslung turbojets and shiny afterburners

● Current ramjets are in the 100,000 hp capability class, says L. E. Dunn of Marquardt Aircraft. One big item in testing is furnishing air for the engine. Static test might need 700 lb of air at 120 psi. To supply this high pressure air might require compressors of 170,000 hp (for continuous operation). A blow-down system is used which has 6 storage vessels with a total capacity of 39,000 cubic feet and pressurized to 250 psi by a 1250 hp compressor plant. Test runs of 45 sec can be made each 1.5 hr. In addition, turbojet engines have been used for exhausters. Fuel flows at tests have been up

to 25 gpm at over 500 psi. For simulation of ram air, heat addition required is about 300 million Btu/hr output for a 45 sec run.

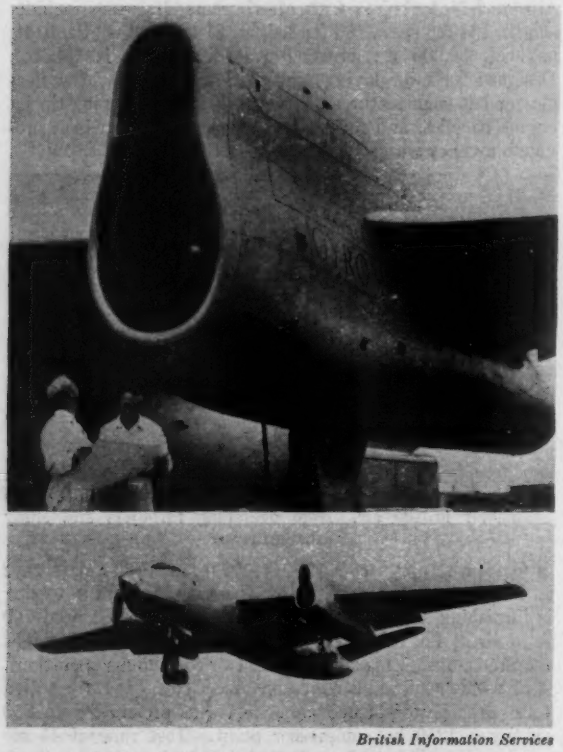
● The Comet 2 has successfully completed trial runs in certification tests for tropical flight. In previous tests, the Comet 2 established an official speed record between London and Khartoum (3068 statute miles) at an average speed of 481 mph. A number of Comet 2's have been ordered by the RAF and deliveries are expected during 1956. The liner is powered by four Rolls-Royce Avon turbojets of 7300 lb thrust each. Loaded weight is 120,000 lb with a payload capacity of 13,000 lb.

● Boeing is to produce 80 502-10C gas turbines for the Navy. The engines will be used to propel two types of small craft and to power generators. 502-10C develops 220 maximum hp as compared to earlier models which deliver 175 hp. In another jet-propelled water vehicle, Donald Campbell hit a top speed of 239.5 mph at Lake Mead, Nev. The 4000 lb Bluebird II averaged 216.2 mph. A 40-ft boat is to evaluate the performance of another turbojet engine, the T-552 "Jupiter." The 1000 lb Solar Aircraft engine develops 50 hp.

● The Canadian Orenda PS-13 turbojet engine is said to be rated at 20,000 lb thrust and has completed over 130 hr in test stand runs.

● Since the end of World War II, some 85,000 turbojet engines have been built by U.S. manufacturers.

● Called the most powerful jet engine in the world, the deHavilland Gyron with a lower thrust level of 15,000 lb thrust is now under active testing. The weight and maximum thrust with afterburner are still secret. The engine is 154 inches long and has an over-all diameter of $46\frac{1}{4}$ inches (less accessories). Present flight tests are being carried out in the Short Sperrin bomber (photo). Gyron Junior, of about 8000 lb thrust, is now under development.



British Information Services

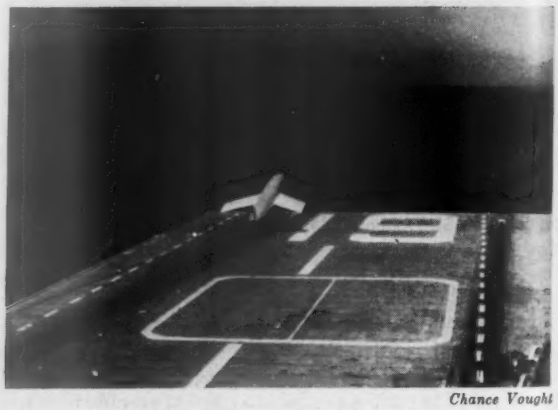
Gyron turbojet. Top, Gyron is in lower nacelle of Sperring. Bottom, Sperrin bomber in flight with Gyron

Rockets, Guided Missiles

Rockets and Missiles. A new launching method has been successfuly employed with the Chance Vought REGULUS, SSM-N-8, missile. REGULUS is mounted on a special, mobile, nonexpendable launching cradle (photo). The cradle can be hooked up to the regular catapult system of an aircraft carrier and launched like any other jet aircraft (photo). The new system eliminates costly RATO bottles and speeds up the launching process. Another Navy missile, the PETREL, AUM-N-2, a Fairchild air-to-underwater guided missile, is now entering the operational stage according to the Navy. The second sub to be converted to guided missile use is the *USS Barbero* (SSG-317). After extensive Pacific training, the sub will join the first US missile-launching sub, the *USS Tunny*. Both subs can launch the REGULUS.

Chance Vought

REGULUS in launching dolly



Chance Vought

REGULUS gets catapult launch

● Six CORPORAL Field Artillery Battalions are departing for Europe after having completed training at Fort Bliss, Tex. Each CORPORAL battalion consists of two batteries and each battery has five launchers. A battalion requires a crew of 250 personnel. The all-weather missile, capable of delivering standard or nuclear warheads, has a range of 50–75 miles. CORPORAL is 46 ft long, has a diameter of 2.5 ft, and grosses about 5 tons. Next larger Army missile under development is the REDSTONE which now has a range reported as 200–400 miles with ultimate range extension to 500–700 miles. The REDSTONE is about 60–65 ft long with a diameter of 5–6 ft; the single-stage rocket is powered by a North American liquid propellant engine which delivers about 70,000 lb thrust, giving it a speed of about 4000 mph. The Army recently announced its intention to develop a larger missile with a range capability of about 1000–1500 miles. Meanwhile, a recent HONEST JOHN firing at the Shimamatsu Bombing Range at Hokkaido, Japan, has thrown light

on the capabilities of the missile. The 27-ft, 6000-lb missile was fired into an impact area 10,000 meters away. Seconds later, the rocket hit the target only 40 meters short of the bull. This December 1955 firing used a concrete warhead.

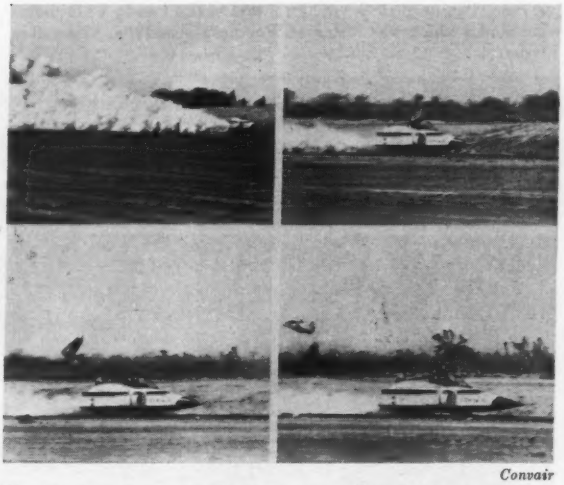
● An additional $7.796^1/_2$ million for research and development work in guided missile control systems was awarded to the Raytheon Manufacturing Co., by the Army Ordnance Corps. The award brings to a total of $17 million since work began in 1953. Work is to continue at Bedford, Mass. The Raytheon missile is reported to be called the HAWK. It is a surface-to-air missile for Army Ordnance and is designed as a low-altitude defense weapon to supplement the NIKE. Other new missiles are the DOVE (Eastman Kodak) for air-to-surface and air-to-underwater purposes; the GOOSE (Fairchild) and CORVUS, both of undisclosed capabilities. DART is an Army antitank artillery missile being developed by the Aerophysics Development Corp.; the latter group was recently made a part of the Studebaker-Packard Corp.

● The Air Force long range missile proving ground in Florida is being expanded. The United States and Britain are expected to agree on extension of the Patrick AFB range to British St. Lucia island (Windward Islands group). This would make possible ranges of 1600 miles. Negotiations are also said to be in progress which would allow extension to St. Helena island off the African coast for testing of an ICBM with a range of 5500 miles. Unofficial reports indicate that facilities for static testing and launching of the ATLAS, SM-65, ICBM are being built at Patrick. Talks with Brazil for establishing a station near Natal (the bulge on the South American coast opposite Africa) were also reported. A 1575-mile long underwater telephone cable was laid by Westinghouse Electric Co. This cable stretches from the Patrick base to Mayaguez, Puerto Rico, is the world's largest. The Florida site has already been selected as the jumping-off place for the VANGUARD program.

● Ballistic rockets and guided missiles are now being "dry-fired" on the new UNIVAC computer at the White Sands Proving Ground. The Remington Rand digital device will simulate the flight of new rockets. In addition to providing for variables not previously quickly calculated, the computer is expected to make actual firings more safe. Recently, a missile booster which was fired at White Sands went off-range and hit a natural gas pipe line near Alamogordo, N. Mex. Another new development at White Sands was reported by the Baldwin-Lima-Hamilton Corp. The calibration system at the 500,000 lb vertical test stand was revealed consisting of measuring and calibrating equipment combined (photo). Hydraulic lines supply a known force to the stand and instruments pick up the force. The system saves calibration time, does not use springs, and gives checks of within 0.1 per cent of actual loads.

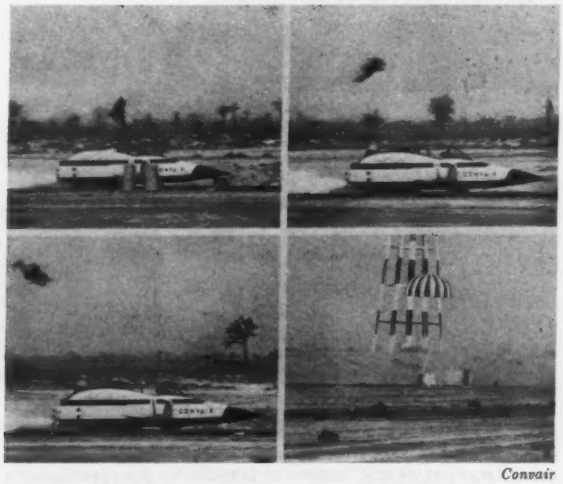
● The Mechanical Test Laboratories of Convair have been conducting ejection tests at the rocket test track at Edwards AFB (photo). The tests are conducted with a 6-ft, 200-lb anthropomorphic dummy in an actual nose section of the F-102A mounted on a rocket sled. The nose section is equipped with the standard pilot escape system for the F-102A. As many as ten 11,000-lb thrust solid propellant rocket motors have propelled the sled during these tests although a maximum of 16 rockets, developing a total thrust of 176,000 lb can be mounted on the sled. A single sustainer rocket motor maintains a constant speed through the ejection phase of the test. The peak velocity of the sled which depends on the number of rockets used, ranging from Mach 0.3–0.98, has been reached in about 3000 ft of track. High-speed cameras, exposing 1000 frames per sec, record the results of the tests. In later tests, a $3000 anthropomorphic dummy with simulated spine, pelvis, and other bony structure, will be subjected to tests.

(Continued on page 194)



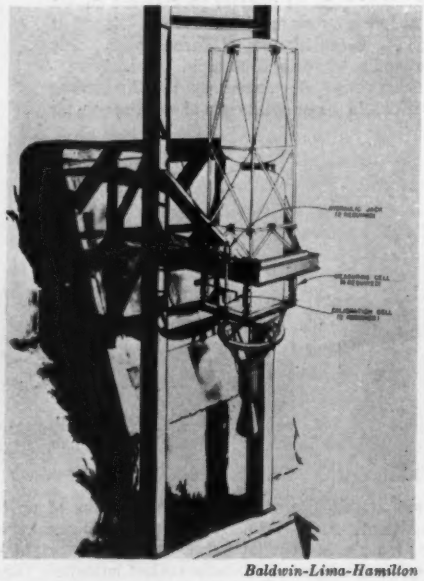
Convair

Ejection sequence. Top left, booster rockets accelerate vehicle. Top right, bottom canopy blasts off, dummy begins ejection



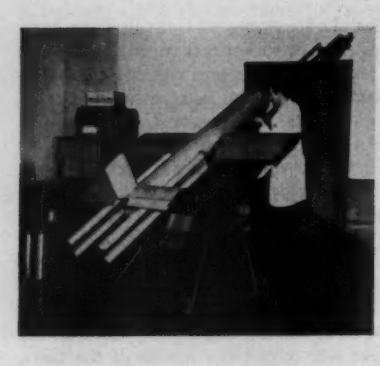
Convair

Dummy in seat is battered but lands safely

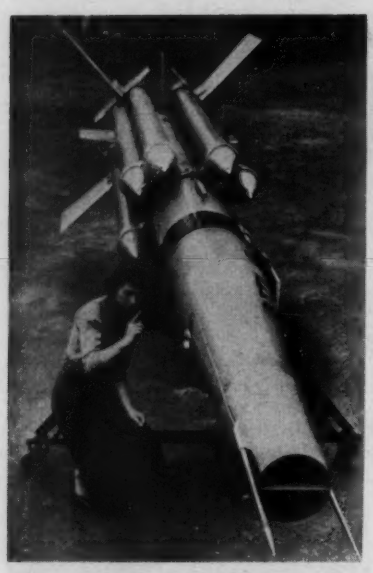


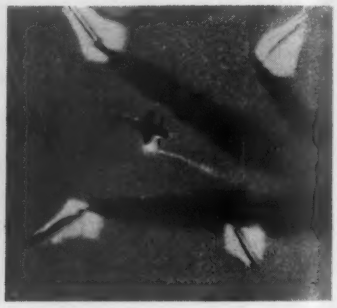
Baldwin-Lima-Hamilton

Thrust measuring and calibration system at WSPG



Left photo shows Britain's first guided missile which was designed and developed in 1945 or 1946 by the Fairey Aviation Co. for the Ministry of Supply. Power comes from four 75-lb thrust rockets of 3-in. diam. Burning time is about 2 sec. Speeds of 200–500 mph were reported. Missile length is 7-ft, $5^1/_2$-in. diam, wingspan is 6 ft 10 in., tail span, 4 ft. A more recent model (ca 1953) is shown in the center; this is the Fairey VTO delta-wing model which was tested at Woomera, Australia. Two Beta rocket motors of 900-lb thrust each are used for sustainers while two 600-lb thrust solid propellant rockets provide launching boost. The Woomera tests were used to study launching aircraft at low accelerations from ramps in near-vertical positions. At right is seen the assembly and electronic check-out of an undisclosed guided rocket by the Ministry of Supply; these models are of more recent vintage which exhibit near mass-production techniques.



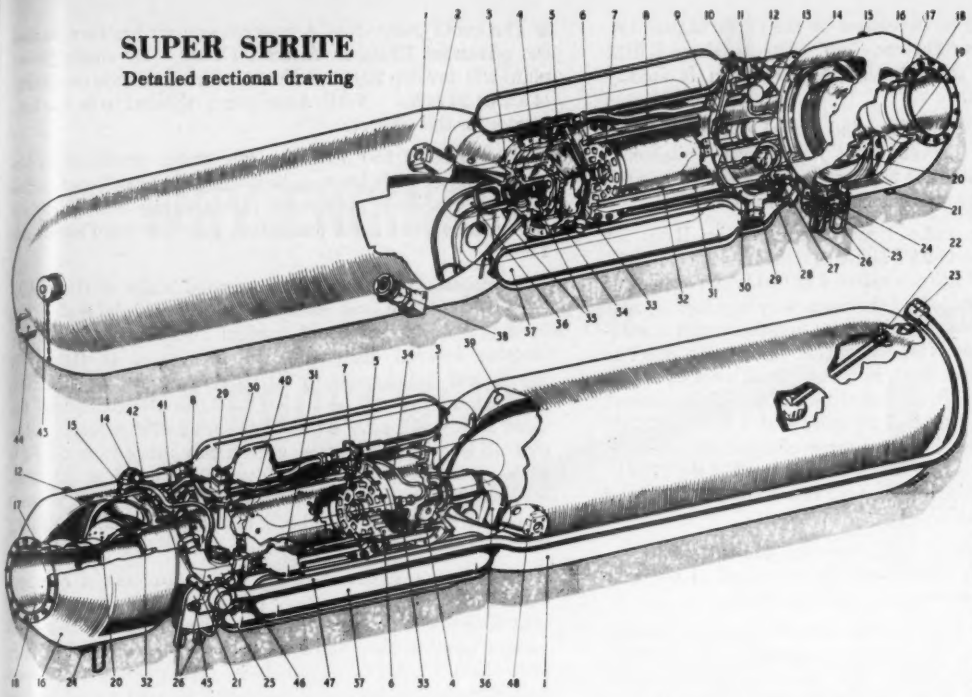


Unique British cluster techniques for booster rockets are shown in this photo group. At left is a new ramjet missile developed at the National Gas Turbine Establishment at Farnborough; this ramjet has a speed capability of about 2000 mph. An early missile using cluster rockets was developed by the Armstrong Whitworth firm (*center*) while the photo at right shows the booster breakaway pattern.

Above photos show a wide variety of missile applications. A two-stage ground-to-air rocket is launched at the left; this firing is at a rocket range in South Wales. Note the large gantry and battery of launchers. No specifications were given on this rocket but other photos have shown launchings at this site of rockets with lengths of up to 20-ft and diameters of 17-in. A guided air-to-air rocket is launched from a Meteor jet fighter (*center*). At right is seen a ground-to-ground 30-tube rocket launcher. The rockets are of 4 to 5-in. caliber.

SUPER SPRITE

Detailed sectional drawing



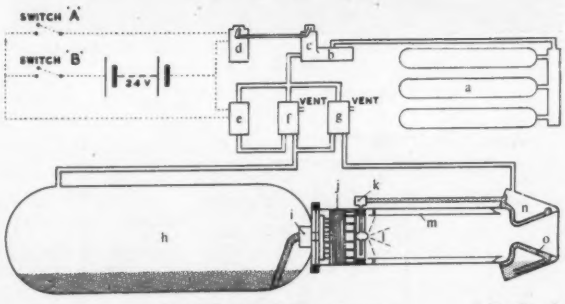
1. HYDROGEN PEROXIDE TANK
2. MAIN TRUNNION MOUNTING FACE, PORT
3. HYDROGEN PEROXIDE CHECK VALVE
4. DISTRIBUTOR PLATE
5. FUEL CHECK-VALVE
6. DECOMPOSITION UNIT RETAINING GRID
7. FUEL INJECTOR
8. FUEL FEED PIPE
9. ACTUATOR
10. CONTROL LINKAGE
11. HIGH PRESSURE NITROGEN FEED PIPE
12. BEARER ARM PORT
13. NITROGEN FILLING PIPE
14. SAFETY AND REDUCING VALVE
15. FUEL TANK NITROGEN INLET
16. FUEL TANK
17. EXPANSION JOINT
18. COMBUSTION CHAMBER NOZZLE
19. FUEL COLLECTOR PIPE
20. COOLANT JACKET
21. BEARER ARM STARBOARD
22. STACK PIPE
23. PEROXIDE TANK NITROGEN INLET
24. FUEL FILLING POINT
25. DISTRIBUTOR AND STARTING VALVE
26. NITROGEN SERVO PIPES
27. NITROGEN FILLING VALVE
28. NITROGEN PRESSURE GAUGE
29. NITROGEN BOTTLE CONNECTOR
30. NITROGEN MANIFOLD
31. COMBUSTION CHAMBER
32. FLAME TUBE
33. CATALYST ELEMENT
34. FUEL INLET PIPES
35. PEROXIDE CHECK VALVE DRAIN PIPE
36. PEROXIDE COLLECTOR PIPE
37. NITROGEN BOTTLES
38. PEROXIDE TANK DRAIN
39. FRONT LIFTING EYE
40. ELECTRICAL FIRING CONNECTION
41. LOW PRESSURE NITROGEN FEED PIPE
42. REAR LIFTING EYE
43. HYDROGEN PEROXIDE FILLING POINT
44. FRONT MOUNTING
45. PEROXIDE TANK VENT
46. NITROGEN FEED PIPE TO FUEL TANK
47. NITROGEN FEED PIPE TO PEROXIDE TANK
48. MAIN TRUNNION MOUNTING FACE, STARBOARD

IN JANUARY 1955, the deHavilland SUPER SPRITE ATO rocket (photo) became the first British rocket engine to receive type approval. Since then, security restrictions have been lifted to reveal details of this new engine. Specifications include:

Total impulse	120,000 lb sec
Maximum thrust	4,200 lb
Firing time	40 sec
Weight, dry	620 lb
Weight, fuelled	1,460 lb
Diameter, over-all	20 1/4 in.
Length	117 1/4 in.
Peroxide tank capacity	57 gal
Fuel tank capacity	5 gal
Nitrogen storage pressure	3,000 psi
Feed pressure	500 psi
Chamber temperature	1,500 C
Mixture ratio (oxidizer:fuel)	20:1
Jettison rate	25 ft/sec
Minimum drop altitude	1,000 ft
Maximum drop speed	250 knots
Life	50 firings

while a schematic drawing (photo) shows the general arrangement. Propellant feed is by 9 nitrogen bottles (*a*). Propellants used are hydrogen peroxide in a stainless steel tank (*h*) and kerosene or wide-cut gasoline in a tank (*n*) around the nozzle. Cockpit controls are *A* and *B*. Both have to be closed to fire. *A* is the safety switch which operates (*c*). Operation of switch *B* opens safety valve (*c*) by means of the actuator (*d*) and lets nitrogen pass to a solenoid valve (*e*) and then to distributor valves (*f* and *g*). The nitrogen feeds to the peroxide tank first. When the tank is at 14 psi, the inlet valve (*i*) opens and allows the peroxide to be sprayed onto the catalyst. A deHavilland spokesman has reported to JET PROPULSION that the catalyst unit is made of silver plated gauze. The catalyst decomposes the peroxide into oxygen and superheated steam at 500–600 C. Engine operation begins with the peroxide alone ("cold"). The fuel valve (*k*) opens at a pressure of 250 psi or about after the engine has been operating "cold" for 1 sec. This action allows the peroxide to enter the engine before the fuel. The nitrogen distributor valves act as vents during filling and standby before firing. Since the engine is only partially cooled, the optimum mixture ratio of 9:1 has been avoided. Inside the combustion chamber a flame tube (*m*) separates the gas flow; the cooler steam and oxygen pass the outer chamber wall while the hotter fuel combustion gases pass down the center. Mixing of the two streams is near the nozzle. The nozzle is regeneratively cooled. The baffles (*o*) keep the fuel in contact with the nozzle. For operation, the pilot closes the first switch (*A*) during the early ground run and switch (*B*) when the critical speed has been reached. After firing, the switches are left open to purge the system of unused propellant. The unit is completely self-contained and is jettisonable for recovery and reuse. Detailed drawings (photo) show the innards of the SUPER SPRITE.

SUPER SPRITE *deHavilland*



SUPER SPRITE schematic *deHavilland*

a. Nitrogen bottles
b. Reducing valve
c. Safety valve
d. Electric actuator
e. Solenoid valve
f. Nitrogen distributor valve
g. Nitrogen distributor valve
h. Hydrogen peroxide tank
i. Peroxide inlet valve
j. Solid catalyst bed
k. Fuel stop-valve
l. Fuel injector
m. Flame tube
n. Fuel tank
o. Baffle

● Second ICBM will be developed by the G. L. Martin Co. at a 4000-acre site near Denver, Colo. The Air Force ICBM is not designated as the WS-107. A 500,000 sq ft facility will house the project.

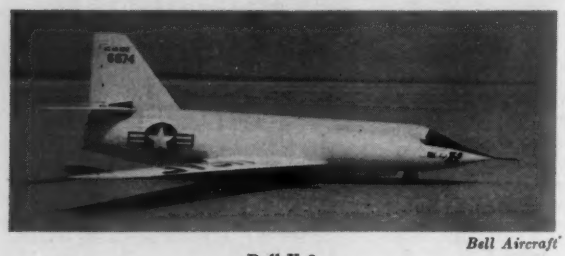
● The Gas Dynamics Facility wind tunnel at the Air Force Arnold Engineering Development Center at Tullahoma, Tenn., has been utilized for testing models of the FALCON, REDSTONE, and the nose cone of the ATLAS.

● A new Air Force contract was announced by Ryan for 1956 production of the Q-2A FIREBEE target drone. FIREBEE has attained an altitude mark of 45,000 ft and a speed of 520 mph. Speculation is that the drone may be pitted against the FALCON in tests. Another such missile contest was recently made when the NIKE was fired against the MATADOR at White Sands. Both hits and misses were recorded. Meanwhile the NIKE B, an improved version of the present missile, may have a range of 50 miles and a speed of 2200 mph. The present version has a range of about 25 miles and a speed of 1500 mph. There is a possibility that the NIKE, SAM-A-7, will be utilized in the near future for the defense of cities and Army installations in Germany.

● During the 1955 fiscal year, order for guided missiles totalled $1,014,077,000. This was 23.7 per cent of the sum allocated for piloted aircraft for the same period.

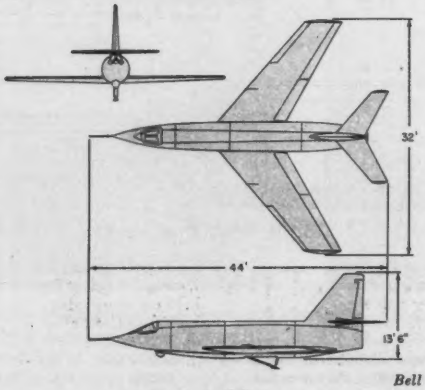
Rocket Aircraft. X-2, the Bell Aircraft supersonic rocket-propelled aircraft has successfully completed powered flight tests at Edwards AFB, Calif. The X-2 was designed to investigate the heat barrier. The new craft is powered by a Curtiss-Wright rocket engine which is designed to exceed the speed of the Bell X-1A which reached a speed of 1650 mph in December 1953. Innovations include: stainless steel and K-monel for fuselage and wings; flat skid landing gear (which allows more fuel to be carried); heavily insulated cabin (pressurized and detachable); and a tempered glass windshield to withstand 1000 F, which is infrared ray resistant. The X-2 is also carried aloft by a mother plane for launching (photos).

● The British Ministry of Supply has announced that the A. V. Roe AVRO-720 turbojet-rocket interceptor development project has been shelved. A similar project, the Saunders-Roe SR-53 is still under development.



Bell Aircraft

Bell X-2



Bell Aircraft

Layout of X-2

● The USAF-Navy-NACA research aircraft has been named the advanced Research Aircraft (X-15). Its single power plant will develop 20,000 lb thrust with an altitude capability of about 50 miles. North American is reported to be the contractor for this project.

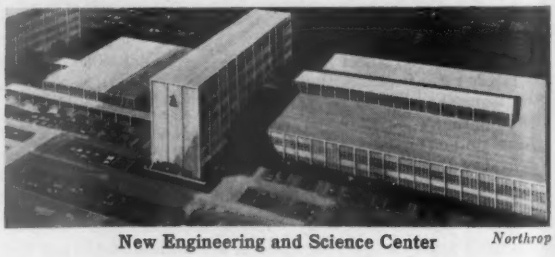
● The Dassault 550 deltawing interceptor combines turbojet and rockets. It has two Armstrong Siddeley Viper turbojets and one liquid propellant rocket engine. The 550 recently underwent flight evaluation tests for the French Air Force.

Satellites. Contract for the second stage of the VANGUARD satellite was awarded to Aerojet-General. The satellite vehicle will be of tandem configuration with decreasing forward diameter. The first stage (airframe by Martin and rocket motor by GE) may resemble the VIKING, the second stage will be similar to the AEROBEE, and the third stage will be a "typical solid propellant rocket." The over-all length of the carrier vehicle may range from 50–75 ft with a gross weight of about 10 tons. As many as 12 satellites may be launched during the 1957–1958 IGY. Present phases of the program are being handled from military funds until Congress appropriates special VANGUARD funds.

● Prof. K. Stanyukovich of the USSR Academy of Sciences Commission on Interplanetary Communications has reported that Russia will be prepared to launch a larger and more advanced satellite than the type proposed by the US shortly after the US satellite is launched. The professor also suggested that directed explosions could be used to advantage in establishing satellites. However, unofficial reports indicate that Soviet work is along more conventional lines. The present Russian program is reported to have reached the development of a final stage, after completion of initial development of the first two stages. Gross weight would range from 75–100 tons, with a first-stage thrust of about 120 tons.

Facilities

NORTHROP AIRCRAFT will begin work shortly on the construction of an advanced engineering research center at Hawthorne, Calif. (photo). In addition to a service center, there will be an engineering test laboratory, a low-speed



New Engineering and Science Center *Northrop*

wind tunnel, and a new cafeteria. The estimated cost is about $8 million and target date for completion is late 1956. A part of the first phase will be the construction for USAF of a new guided missile engine test facility. Some of the projects that will be undertaken by Northrop at the new facility will be exploration of the "thermal barrier," new types of guided missiles, and problems related to space flight. Guided missile airframes and engines will be tested in a low-frequency noise modular test cell with an all-enclosed sound muffler.

● Advanced aircraft engines will be engineered by the Allison Division of General Motors at a $75 million research and development facility at Maywood, Ind.

● Additional property for expansion has been provided for in a recent purchase by the Ramo-Wooldridge Corp. near the Los Angeles International Airport. Construction on the new site will begin this year.

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INDUSTRY'S USE OF 16MM CAMERAS BROADENS

Northrop Aircraft Demonstrates Expanded Industrial Use of Mitchell Cameras

Over 100,000 feet of film were shot last year by two 16mm Mitchell cameras operated by a full-scale motion picture unit at Northrop Aircraft. Operating daily throughout the year, these 16mm cameras provide impressive evidence of the rising role of professional motion picture equipment in American Industry today.

Northrop, a leader in airframe and missile manufacture, makes diversified use of their Mitchell cameras. Motion pictures range from employee activities to engineering test films—where re-shooting is impossible and where steady, accurately-framed film of superior quality is consistently delivered by Mitchell cameras.

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Alaska Bound test pilot Bob Love and Columnist Marvin Miles being filmed by Mitchell camera for Northrop Public Relations Department.

For Quality Control Film, Mitchell camera moves in for close shots of Scorpion F-89D.

104 Rocket Salvo of twin-jet F-89D is captured on 16mm Engineering Test film.

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ARS News

Furnas to Speak at Los Angeles Conference

C. C. FURNAS, Assistant Secretary of Defense for Research and Development and Fellow Member of ARS, will be the banquet speaker at the ARS-ASME Aviation Division Conference in Los Angeles, March 15.

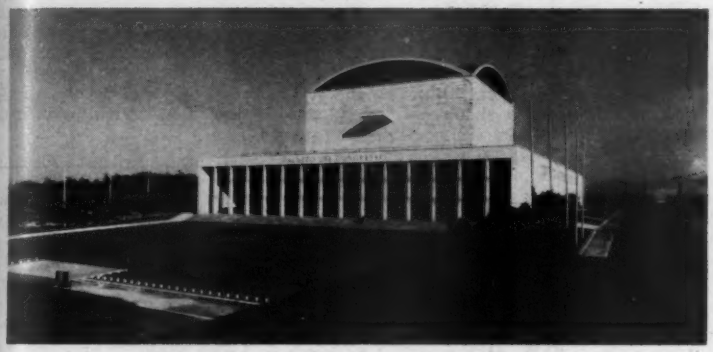
Furnas is former chancellor of the University of Buffalo and director of the Cornell Aeronautical Laboratory.

Speaker at a luncheon to be held on the first day of the March 14–16 meeting will be Major General Roy H. Lynn, Commander, Western Air Defense Force, Hamilton AFB, Calif.

At a luncheon on March 15, five chief test pilots from California aircraft firms are scheduled to participate in a panel on "What I Want Most from the Engineer."

Twenty sessions will be held during the meeting—on Air Cargo, Instrumentation, Thermal Thicket, and Earth Satellites. ARS has organized three of the sessions, the program for which was carried in the February issue of JET PROPULSION.

Rome's Palazzo dei Congressi



Site of Seventh IAF Congress, September 15–21

ARS Delegation Planning Trip to Include Farnborough Air Show, European Tour en Route to Meeting

A special flight is being organized by ARS for members attending the Seventh Annual Congress of the International Astronautical Federation, scheduled for September 15–21 in Rome.

The plane will leave New York for England on or about September 1 in time for the Farnborough Air Show which will be held during the first week in September.

An optional tour will be planned, covering Paris, Switzerland, and Italy, during the period between the Farnborough demonstration and the commencement of the Congress at the magnificent Palazzo dei Congressi, Rome, on September 15. The return trip to New York will be on September 22.

ARS members and guests interested in joining the group should contact James J. Harford, American Rocket Society, 500 Fifth Avenue, New York 36, New York, for details, as soon as possible.

The provisional program is as follows:

Saturday, September 15	
10:00 a.m.	Meeting of Council and Committee Chairman (Meeting open to Delegates)
Sunday, September 16	
2:00 p.m.	Registration
7:00 p.m.	Informal meeting of Congress participants
Monday, September 17	
8:00 a.m.	Plenary Session
3:00 p.m.	Plenary Session
8:00 p.m.	Film Show
Tuesday, September 18	
10:00 a.m.	Official Opening of Congress
11:00 a.m.	Opening Paper
12:00 p.m.	Press Conference
3:00 p.m.	Technical Session
Wednesday, September 19	
9:00 a.m.	Technical Session
3:00 p.m.	Technical Session
Thursday, September 20	
9:00 a.m.	Technical Session
3:00 p.m.	Technical Session
8:00 p.m.	Social Dinner
Friday, September 21	
8:00 a.m.	Delegates Plenary Session
3:00 p.m.	Delegates Plenary Session

Three Hundred Hear ARS Papers at IAS Meeting

MORE than 300 people attended an ARS session on Rocket Propulsion at the 24th Annual Meeting of the Institute of the Aeronautical Sciences in New York, January 24. Chairman of the session was D. F. Ferris, Chief, Preliminary Design, Reaction Motors, Inc. A summary of the papers follows:

"Demonstration of Reliability in Liquid Propellant Rocket Engines," Albert G. Thatcher, Chief, Projects Operations Dept.; H. A. Barton, Asst. Project Engineer; Reaction Motors. (Preprint 284–56.)

Conditions which make it difficult to achieve high reliability by usual methods of flight testing indicate the desirability of obtaining preflight reliability data of missile components. The solution, in part, can be realized by including a statistical reliability development and evaluation plan in the development program. This paper outlines how the effort to achieve specified reliability should be felt in the design phase, the development testing phase, the proof testing phase, and the reliability demonstration phase of a development program.

"Ballistic Missile Performance," J. Wm. Reece, R. David Joseph, Dorothy Shaffer; Cornell Aero. Lab. (Preprint 283–56.)

A semianalytic method is derived for calculating the range of one-stage ballistic rocket-propelled surface-to-surface missiles. The method consists of obtaining analytic solutions to the equations of motion, supposing flight in vacuum, and then correcting these solutions for the effect of drag. Both the velocity at thrust cutoff and the range following cutoff are handled in this manner.

"Improved On-Off Missile Stabilization," Robert W. Bass, Research Asst., Dept. of Mathematics, Princeton Univ. (Preprint 285–56.)

In a new synthesis procedure for on-off control systems presented, delays due to time-lag and hysteresis in the relay or contactor can be completely eliminated. This is readily affected by adding feedback from the on-off element itself to the conventional error and error-derivative feedbacks. An explicit algorithm is developed, according to which the ideal feedback coefficients of a "perfectly" stabilized servo system can be read off directly from the equations of the corresponding conventional system.

Bender Hits Lack of Research in Aviation

WELCOME W. BENDER, vice-president of RIAS, Inc., newly formed research subsidiary of the Glenn L. Martin

Company, Baltimore, told the ARS Princeton Group on February 2 that the aircraft industry is "starving for ideas."

He pointed out that only about 1/10 of 1 per cent of the national budget is spent on research. "Although the aircraft industry is supposed to be using about 30 per cent of the nation's scientific brain power," he said, "new airplanes and missiles are simply extrapolations of last year's designs."

Bender, former head of Martin's electronic department, stated that university research is inadequate to feed the volume of fresh ideas demanded by our economy and that industry must help substantially.

He felt that fundamental research should be an "economically potent force."

RIAS is undertaking investigation of the research possibilities in gravity, solid state physics, quantum mechanics, meteorology, upper atmosphere, and other areas.

Bender was introduced by Chairman J. P. Layton.

Ramo, ICBM Expert, To Speak at Princeton, April 5

SIMON RAMO, executive vice-president of Ramo-Wooldridge Corporation, Los Angeles, will deliver an address at Princeton University on April 5. The talk will be sponsored jointly by ARS and the University's Department of Aeronautical Engineering. Several other technical societies have been invited to cosponsor the meeting.

Dr. Ramo, whose organization has prime systems responsibility for the development of ICBM Atlas, will deal with the nature and future of missile development. He will speak on a particularly timely topic—the changing relations between scientists and engineers caused by the onset of the weapons system concept.

The meeting will be held at Princeton's Palmer Physical Laboratory at 8:00 P.M.

Seven New Corporate Members Bring Total to 68

RECENT applicants for Corporate Membership in ARS include two jet engine manufacturers, two specialists in guidance and control systems, one solid propellant producer, one company which makes both liquid and solid propellants, and a manufacturer of missile accessory equipment.

The companies, the activities they have relating to ARS, and the individuals chosen to represent them are as follows:

Allison Div., General Motors Corp., Indianapolis 6, Ind. Jet and turboprop engines. D. Geran, director of engineering; R. S. Hall, section chief, Preliminary Design; C. J. McDowall, chief engineer, and J. B. Wheatley, asst. chief engineer, Advanced Design & Development; and J. E. Knott, asst. sales manager, Aircraft Engines.

Ford Motor Co., Scientific Laboratory, P. O. Box 2053, Dearborn, Mich. Propulsion systems, instrumentation, control systems, high temperature materials, aerodynamics, structures, combustion fuels and propellants, heat transfer, etc.. A. A. Kucher, Director; Michael Florence, Jr., and Donald N. Frey, associate directors; Adolph Egli, Basic Engineering Dept.; and Eugene F. Hill, manager, Chemistry Dept.

Hoffman Laboratories, Inc., 3761 Hill St., Los Angeles 7, Calif. Infrared, radar, and inertial guidance and control systems; over-all missile system planning, J. B. Moss, president; C. Wasmansdorff, vice-president, Engineering; W. R. Bush, asst. general sales manager; L. C. Downes, research Development head; and T. C. Clark, staff assistant to the vice-president.

Olin Mathieson Chemical Corp., 460 Park Ave., New York 22, N. Y. Liquid and solid propellants; oxidizers and materials of fabrication. Harry A. Sosnoski, aviation adviser to the president; Dr. L. Kermit Herndon, director of government chemical research; Dr. J. H. McLain, director of government liaison; J. J. O'Neill, asst. to the vice-president of the Explosives Div.; and R. S. Rippe, sales manager.

Phillips Petroleum Co., Rocket Fuels Div., McGregor, Tex. Large-scale development and manufacturing operations of solid propellant rockets. E. A. Malick, manager, and L. A. Maciula, asst. manager, Rocket Fuels Div.; E. F. Fiock, technical director; J. A. McBride, asst. technical director; and F. M. Files, manager, Manufacturing Branch.

Connecticut Valley Section Gets Charter

Shown at the charter presentation meeting of the Connecticut Valley Section are (left to right): Robert Mitton, vice-president (flight test engineer, Kaman Aircraft); Chester Hayes, treasurer (Kalart, Inc.); Sheldon Dolinger, secretary (analysis engineer, United Aircraft Corporation Research Department); J. B. Cowen, national director; Major Charles Arvin; Charles H. King, Jr., president (head, Combustion Section, United Aircraft Corporation Research Department); Frank W. Caldwell, director (retired director of research, United Aircraft Research Department); and Martin Stevens, director (chief of preliminary design, Kaman Aircraft).

Mr. Cowen, of Aerojet General, presented the Charter to this 23rd Section of ARS which covers a circular area of 50 miles with Hartford as the center. Major Arvin, of the Headquarters First Anti-Aircraft Command, was guest speaker.

Jolliffe, Rizk Speak at Florida Section Meetings

R. S. Mitchell, president (division manager, Pan American Guided Missile Range) (left), C. B. Jolliffe, (vice-president and technical director of RCA) (center), and V. O. Smith, vice-president (manager, Northrop Missile Test Facility) (right) are shown at a recent meeting of the Florida Section at Patrick AFB.

Dr. Jolliffe spoke on RCA's progress in electronic research.

Right photo shows Kaleel S. Rizk (center), speaker at a January meeting, with Smith (left) and Paul Campbell, secretary (Boeing).

Rizk is deputy director of range development at the Air Force Missile Test Center, Patrick AFB. He discussed problems in trajectory measurement of long-range missiles.

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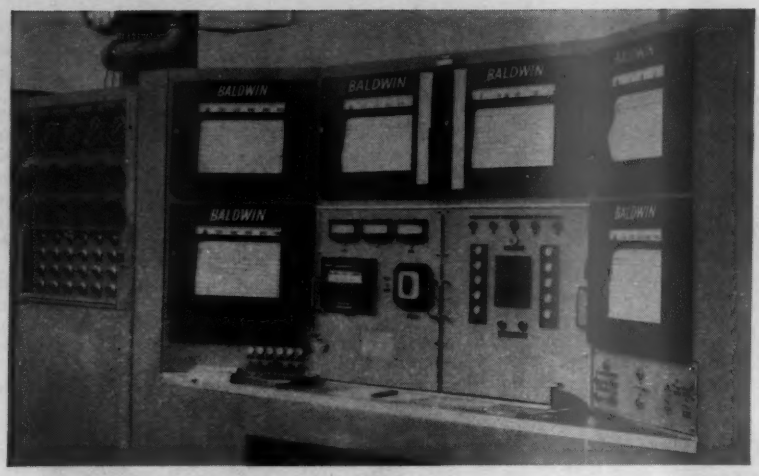

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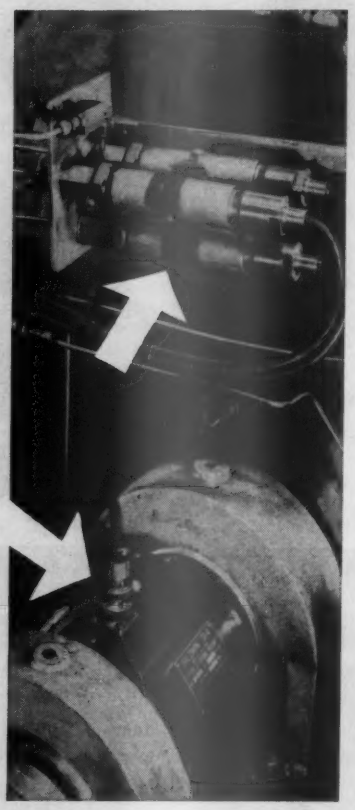

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H. A. Wagner Co., 14707 Keswick St., Van Nuys, Calif. Development of missile systems, such as guidance, tracking, and training systems. H. A. Wagner, president and chief engineer; N. Mastrocola, project engineer; and R. N. Lahde, chief system test engineer.

Leach Corporation, 5915 Avalon Boulevard, Los Angeles 3, Calif. Manufacturers of relays, power supplies, and other accessory equipment for guided missiles. The individuals chosen to represent Leach are: K. F. Julin, executive vice-president and general manager; J. L. Elliott, assistant to general manager; E. K. Neale, vice-president, engineering; R. B. Hutton, vice-president, sales; and S. L. Bradley, chief development engineer, Inet-Palmer Division.

Section Doings

Alabama. British Army Warrant Officer H. W. Eastland, stationed at the Woomera Guided Missile Range in South Australia, addressed the January meeting at Huntsville. Photographs of several British missiles were shown. Members were particularly interested in comparing notes on living conditions in U. S. desert country and those on the other side of the world.

Arizona. At the February meeting, a lecture was given on the basic theory of rocket flight by Ed Meyer, followed by a film entitled "On to Jupiter." Charles J. Green of Hughes Aircraft, Tucson, is president of the Section which now has 36 members.

Chicago. Officers elected for 1956 are: president, Gerald M. Platz; vice-president, John Krc, Jr.; secretary, Andrew A. Affrunti; and treasurer, Dusan J. Ljubenko. Board of Directors: Vincent J. Cushing, Layton C. Kinney, and Stephen J. Fraenkel.

Cleveland-Akron. At the February meeting in Cleveland, S. Fred Singer described designs and applications of artificial earth satellites, including Project VANGUARD.

Radio Station WSRS in Cleveland Heights has joined Station WHBC in Canton and WJW in Cleveland in carrying 15-minute recorded interviews prepared at each meeting. An interview with Navy Commander J. Fisher at Thompson Products was broadcast by Station WJW. Commander Fisher gave a general talk on rocket firings from the Norton Sound.

Columbus. Fifty-five persons attended the January meeting of this proposed Section. Alexis Lemon, Assistant Head of the Chemical Engineering Department at Battelle, spoke on rocket engine performance and results using various propellant combinations. There are ten active members in the area and 13 new membership applications.

Fort Wayne. Officers elected for 1956 are: Lloyd R. Wadekamper, president; Jerry Fogel, vice-president; Paul Kruse, secretary; and Marion B. Stults, treasurer. Directors: Michael Katanik, Rex Pierson, Richard Hart, Robert Marie, Norman Baker, Robert Censak, and George Kraick.

Indiana. With the February issue, the Indiana Section initiated a regular ARS

News Letter, edited by A. R. Graham and a staff of five. It contains announcements and accounts of activities, an article on research at Purdue University Jet Propulsion Center, and an item describing the work being done by the propulsion section of Convair's Fort Worth Division.

New York. Election of officers took place at the January meeting. Charles J. Marsel was elected president; Paul M. Terlizzi, vice-president; Rudolph L. Graupe, secretary, and Charles G. Sage was re-elected treasurer. Plans were made for monthly meetings, and a field trip in May.

Pacific Northwest. More than 600 people attended a December 9 meeting at which the guest Speaker was Joseph Kaplan, Chairman of the U. S. National Committee for the IGY. His subject was rocket and satellite studies. Dr. Kaplan was introduced by Robert H. Jewett, chief engineer of Boeing's pilotless aircraft division, recently awarded a Fellow Membership in ARS.

Southern California. Three separate field trips to various NIKE firing sites were features in the January program. Sites included El Monte, Van Nuys, and San Pedro. Each trip was limited to 50 members.

Southern Ohio. New officers (all of General Electric) are: W. C. Cooley (Aircraft Nuclear Propulsion Department), president; T. P. Meloy, (Jet Engine Department), vice-president; Milt. Dowell (Aircraft Gas Turbine Department), secretary; and Connie Pope, treasurer. Directors for 1956–1957 are: J. T. Marshall (Bendix, Hamilton Division), G. McTigue (General Electric) and W. J. Mizen (Bendix, Hamilton Division). Directors retained from 1955 to serve this year are: Allen Beverage (General Electric), H. R. J. Grosch (General Electric), and G. Richard Lott (Reaction Motors, Inc.).

Univ. of Michigan. Officers of the recently organized Student Group are: president, Richard Signor; vice-president, J. B. Bullock; treasurer, Clifford Robinett; recording secretary, Bradford Barr; corresponding secretary, Herbert Arkin, Jr.

Monopropellant Committee's First Report Available

First report from the ARS Committee on Monopropellant Test Methods is now ready. *Recommended Test No. 1—Card Gap Test for Shock Sensitivity of Liquid Monoproplellants* is a 21-page document (with stiff cover) including tables, diagrams, and photographs. The test described measures the minimum hydrodynamic shock required to produce a stable propagation of a high order detonation in a 1-in. steel pipe. Principal advantages are the practical scale of the test, the freedom of results from ambiguous interpretation, and the moderate material cost.

The report is based on experimental work by G. D. Edwards and T. K. Rice at the U. S. Naval Ordnance Laboratory, White Oak, Maryland. It was written by Edwards and was presented to the Committee by E. C. Noonan, chief, Fuels and Propellants Division, Explosives Research, at NOL. It may be obtained from the AMERICAN ROCKET SOCIETY, 500 Fifth Avenue, New York 36, N. Y., at a cost of $1 per copy.

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6400, 11400, 24300 Series . . . AC, DC, 400 cycle.
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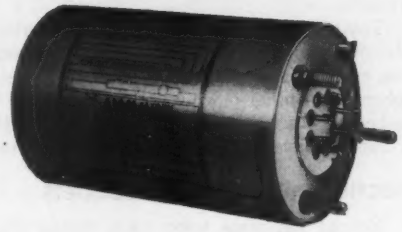
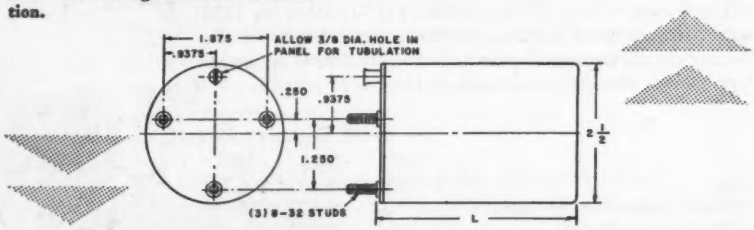
Standard unit withstands vibration of 5-55 CPS at 10g maximum acceleration.



• 6400, 11400, 24300 SERIES DIRECT CURRENT, ALTERNATING CURRENT, 400 CYCLE. TIME DELAY SETTINGS FROM 2 SECONDS TO THREE HOURS • SWITCHING FROM 15-100% OF OVERALL INTERVAL CAN BE SUPPLIED • MEET MILITARY ENVIRONMENTAL SPECIFICATIONS • FILTERING TO MEET MIL-I-6181B OPTIONAL ON DC UNITS • WIRING DIAGRAM ON CASE

LENGTH "L" MAX.	6400 SERIES STANDARD D.C.	6400 SERIES GOVERNED D.C.	24300 SERIES 400 CYCLE A.C.	11400 SERIES 50,60 CYCLE A.C.
2 OR 3 SWITCHES	3 9/16	4 7/32	3 9/16	3 9/16



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3600, 13600, 24400 Series . . . AC, DC, 400 cycle.
Motor-driving cam shaft principle actuates switches in accurately repeating sequence.
Motor output speeds: 10 RPM — 1 revol. per 2 hrs. in 5300 and 5600 series.
1 revol. per 40 minutes for 5800 series.
1 revol. per day for 60 cycle type.
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Accommodates up to 10 switches.
DC Motors protected against reversed polarity. Filtering provided to meet MIL-I-6181 specification.
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LENGTH "L"	3600 SERIES STANDARD D.C.	3600 SERIES GOVERNED DC.	24400 SERIES 400 CYCLE A.C.	13600 SERIES 50,60 CYCLE AC.
1 SWITCH	2 27/32	3 17/32	3	2 31/32
2 SWITCH	3 5/16	3 7/8	3 1/4	3 5/16
3 SWITCH	3 1/2	4 5/16	3 9/16	3 5/8

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TREASURER'S REPORT—YEAR 1955

INCOME AND OUTGO

Receipts amounting to $139,073.76 were recorded for the year 1955, representing a 72.2% increase over 1954 and a 204.4% increase over 1953. Journal income (advertising, subscriptions, and reprints) amounted to $74,121.66, accounting for 53.3% of total receipts for the year. Membership dues increased to $55,428.82, representing 39.8% of total receipts.

Total disbursements for the year amounted to $137,203.08. Journal printing and engraving, editorial costs, and advertising commissions totaled $65,927.98; office salaries, rent, telephone, and other office expenses totaled $39,434.80; and all other expenses, $31,840.30 including $26,119.69 for Section refunds, conventions, postage, stationery, and the roster.

SECTION REFUNDS AND BUDGETS

Refund payments were made during the year based on paid-up members through 30 September 1955. The final computation through 31 December 1955 was made in February 1956. Advance payments were made to Sections during the year as requested. Your Board of Directors, at the annual meeting in Chicago, authorized a minimum 1956 refund payment of $100 for all Sections and established policies for reviewing Section performance and budget requests, which will be included in a Section Manual soon to be published.

FINANCIAL CONDITION

The Society's financial statements as of 31 December 1955 reflect the strongest financial condition ever attained by the Society during its long 25-year history. Condensed comparative balance sheet results are shown below:

	Year ended December 31st		
	1953	*1954*	*1955*
Cash	$ 1,839	$ 2,840	$ 4,711
Accounts receivable (less reserve)	8,610	9,903	13,190
Inventories (estimated)	3,974	2,431	1,300
Furniture & equipment (at cost)	1,092	4,399	5,579
Special funds	470	966	1,723
Total assets	$15,985	$20,539	$26,503
Accounts payable	$10,789	$10,406	$ 3,902
Balance—net worth	5,196	10,133	22,601
Total liabilities and net worth	$15,985	$20,539	$26,503
Cash and receivables less liabilities	$ (340)	$ 2,337	$13,999

Increase receipts for the year not only covered the heavy expenditures authorized and incurred under the "Journal" expansion program initiated during the year but were sufficient to substantially reduce Accounts Payable which, at the year end, amounted to $3902, including an estimated $1800 owing Sections for Refunds and $300 for I.A.F. 1955 dues.

Inventories represented by books, preprints, binders, and pins, etc., were maintained at a modest level in line with the demand for such items, total sales of which amounted to $5517 for the year.

Special Funds represented by cash and Government bonds include the A. G. Haley Endowment Fund (Astronautics Award) and Other Awards Fund amounting to $714 and $1009, respectively.

ANNUAL AUDIT AND SYSTEMS STUDY

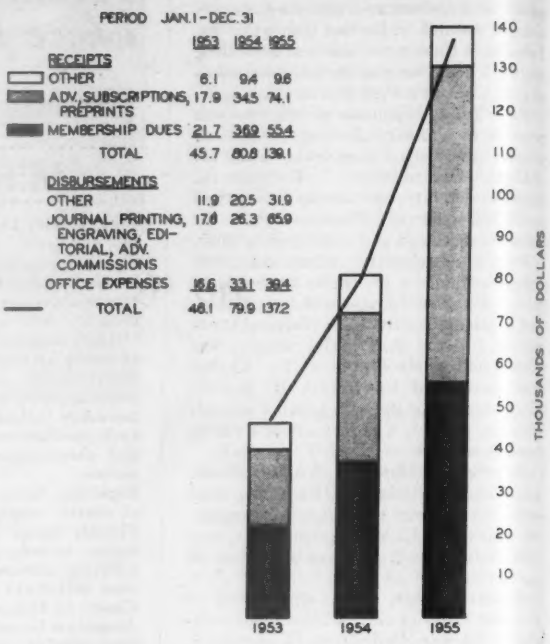
An audit of the Society's recorded cash transactions was conducted for the years 1953 and 1954 by the public accounting firm of Ernst and Ernst. In addition, the Management Service Division of Ernst and Ernst performed a systems study for the National Office during the year. Significant changes in accounting procedure, roster control, and office routines have been made for 1956.

Detailed financial statements for the years 1952 through 1955 are available to all members. Requests should be forwarded to our Treasurer, Mr. Robert M. Lawrence, Reaction Motors, Inc., Denville, N. J.

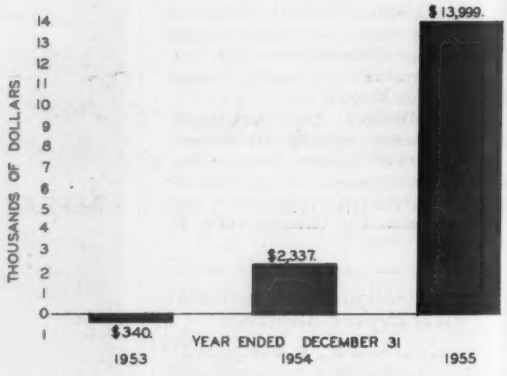
FINANCIAL OUTLOOK FOR 1956

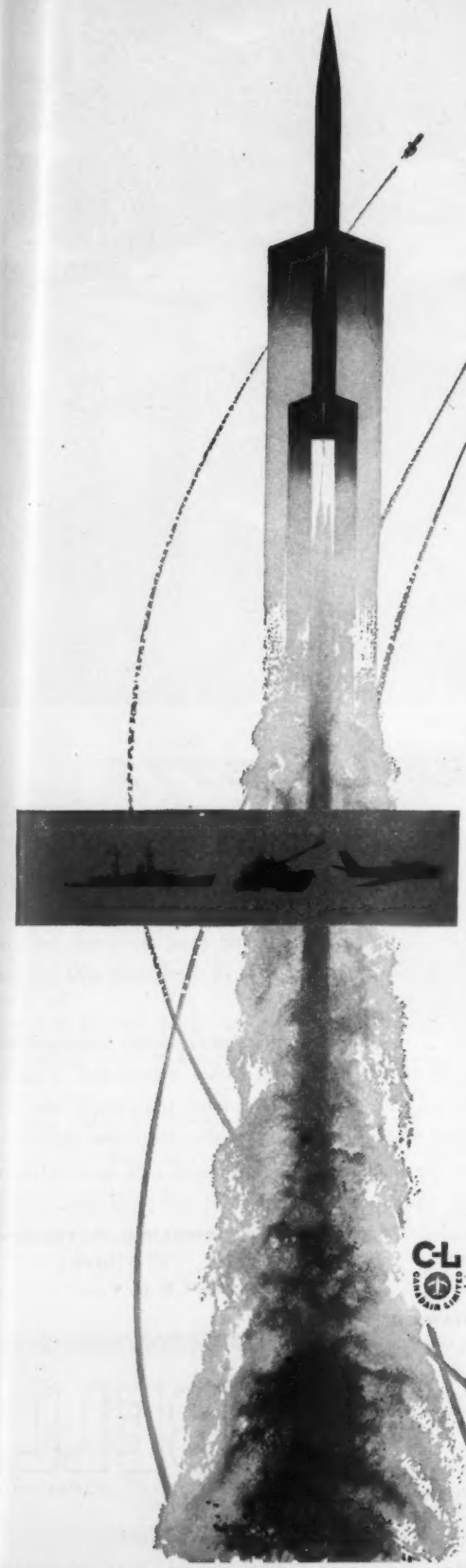
The preliminary "Income Forecast and Expense Budget for 1956" approved by the Board of Directors in November at the Annual Convention in Chicago indicates that total receipts should increase at least 25% over 1955. Expenditures will be closely controlled and maintained within the projected 1956 income level.

Receipts and Disbursements



Cash and Receivables Less Liabilities





FASTER FARTHER HIGHER

The development of guided missiles of every type is becoming one of the most competitive areas in our world today . . . for supremacy in this field can well determine peace for many years. The race is now for greater speed, higher altitude, longer range, more sensitive control.

The strength of Western defense lies to a great extent in the development for the Armed Forces of these new weapons systems suited to the supersonic age. The once deadly cannon, machine gun and rocket are being superseded by complex weapons of great ingenuity.

Canadair has long had a prominent role in Canada's guided missile program, applying the knowledge acquired in years of experience in advanced aircraft systems engineering . . . and Canadair's research, engineering and manufacturing resources are constantly making further important contributions to projects in this field.

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FUTURES AT *Fahrenheit* 5772

Futures in rocket propulsion at Bell Aircraft are as hot as the temperature in the rocket combustion chambers. Bell's rapidly expanding rocket engine division provides a wide latitude for individual growth in rocket engineering.

Eleven years of designing and building liquid-fuel rocket power-plants has given Bell a broad background of experience in both research and production. Working with complete systems . . . thrust chambers, turbine pumps, control systems, pressurization systems, and tanks . . . Bell has designed and developed a number of successful rocket engines for different Army, Navy, and Air Force projects, including the Nike and Rascal guided missiles.

In research, Bell has experimented with over 20 different rocket propellants . . . ceramic lined thrust chambers . . . improvements of existing materials for higher performance . . . and an exhaustive study of combustion processes. Available are complete research and production test facilities, including 44 test cells capable of conducting 400 test runs a month.

This is the opportunity for you to become associated with some of the finest minds in rocket engineering. Advanced projects assure you of professional recognition and high financial rewards depending on your individual ability.

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GROUP ENGINEER—HEAT TRANSFER AND FLUID MECHANICS
To plan, supervise and perform analytical and experimental studies on heat transfer phenomena associated with rocket engines; film and transpiration cooling; liquid injection studies, acoustic phenomena.

AERONAUTICAL AND MECHANICAL ENGINEERS
For design and development of complete rocket engines and components; analyze test results to evaluate engine performance; design and administer test set-ups.

ROCKET TEST ENGINEERS
For component, thrust-chamber, research and complete rocket engine test.

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Equipment

Electrical, Electronic

Corrosion Resistant Thermocouple. Flexible neoprene conduit with metal fittings. Conax Corp., 7811 Sheridan Drive, Buffalo 21, N. Y.

High Temperature Transducer. Made of barium titanate and permits operation up to 125 C, increases range of high frequency ultrasonic equipment. McCenna Laboratories, 2503 Main St., Santa Monica, Calif.

Thermocouple for Double Wall Chambers. Data sheet SM-6 covers stainless steel packing glands. Conax Corp., 7811 Sheridan Drive, Buffalo 21, N. Y.

Pickup. Transducer converts mechanical motion into electrical impulses. Model 3010-A indicates rpm, angular, and linear motion. Electro Products Laboratories, 4505 N. Ravenswood Ave., Chicago 40, Ill.

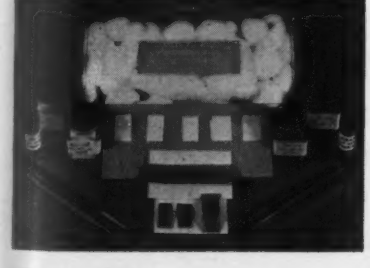
Fuel Level Switch. For balancing, tank switching, or fuel management. (photo) Thermistor element. Operates at −65 F to +200 F. Power is 0.13 amp and 28 VDC. Weight is 0.4 lb. Avien, 58-15 Northern Blvd., Woodside 77, N. Y.

Pressure Compensator. For bleed systems in turboprops or turbojets. Sizes up to 8 in. ID. Arrowhead Rubber Co., Metal Products Div., 2310 Curry St., Long Beach, Calif.

Pressure Indicator. For aircraft and rocket engines. Crystal quartz transducer ranges up to 20,000 psi. Kistler Instrument Co., 15 Webster St., Tonawanda, N. Y.

Inertial Mass Flowmeter. Constant speed drive. Readout system features self-balancing bridge with analog or digital output. Inertial Instruments Inc., 2029 Broadway, Santa Monica, Calif.

Strain Gage Kits. Do-it-yourself kit for making high-temperature strain gages. Cements offer limits of 700, 900, 1100, and 1800 F. 10 gages included. Baldwin-Lima-Hamilton Corp., Philadelphia 42, Pa. (photo).



High Speed Impulse Recorder. Interval and impulse durations of rapid fire armaments can be recorded on dry paper. Measures impulse down to 1 millisec and 1 millisec between pulses. PSC Applied Research Ltd., 1500 O'Connor Drive, Toronto, Canada.

DKO Keyer-Subcarrier Oscillator. For pulse width multi-channel coding in FM/FM telemetering systems. Weight is 8 oz. DKA-1 PW Keyer-Record Amplifier for multi-coding and direct recording onto magnetic tape. Miniaturized Rotary Sampling Switch for airborne and general instrumentation. Model DPA-1 RF Power Amplifier for use in 215–235 mc telemetering band. Applied Science Corp. of Princeton, Box 44, Princeton, N. J.

Mechanical

Laboratory Roll Mills. 6 in. × 12 in., and 6 in. times 13 in. experimental mills for rubber, plastics. Stewart Bolling & Co., 3190 E. 65th St., Cleveland 27, Ohio.

Liquid Oxygen Storage. Model LOX 150 is skid mounted, weighs 890 lb, stores 150 gal liquid oxygen in insulated vacuum tank. Model LOX 500-1, also on skids weighs 2480 lb, stores 500 gal. Model LOX 50-2 (USAF-type) is trailer mounted, weighs 1000 lb. and stores 50 gal (photo); Model LOX 50-3 also stores 50 gal but is Navy-type weighing 1106 lb.

Metering Valves. Models offer pressures to 6000 psi, operation at −100 to +500 F, fingertip control. Made in aluminum, brass, and stainless steel. Robbins Aviation, 1735 W. Florence, Los Angeles 47, Calif.

Test

Data Converter. Model E Datrac can be used for digital to voltage or vice versa with accuracy of ±1% or ±1 digit. Epsco, Inc., 588 Commonwealth Ave., Boston 15, Mass.

Jet Engine Control Tester. Two chillers for air inlet and refrigeration systems. American Research Corp., 11 Brook St., Bristol, Conn.

Hole Micrometer. Measures by 0.0001 in. for bores $^{3}/_{16}$ in. to 1.6 in. and in depths up to 6 ft with extension. Automatic alignment. English or Metric. Alina Corp., 401 Broadway, New York 13, N. Y.

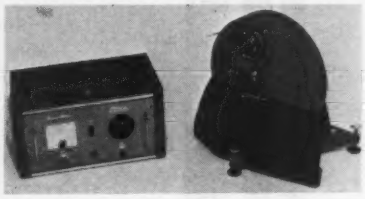
Missle Altitude Test Box. Simulates up to 350,000 ft. Model 5500 Iono-Chamber. 30 in. deep by 18 in. ID. Hudson Bay Div., Labline Inc., 3070 W. Grand, Chicago 22, Ill.

Test Chamber. For altitude (sea level to 100,000 ft), temperature (−100 to +500 F) and humidity (20–95% RH). 5 cu ft, to 64 cu ft sizes. American Research Corp., 11 Brook Street, Bristol, Conn. (photo).

Vibration Machine. Frequency range of 5–2000 cps. True linear displacement of 1 in. 8-in. test table. MB Manufacturing Co., Engineering Dept., 1060 State St., New Haven, Conn.

Test Centrifuge. Lab model provides variable control from 4–400 G. Electric tachometer reads speed ±0.1%. Coleman Engineering Co., 6040 W. Jefferson Blvd., Los Angeles 16, Calif.

High-Speed Rotating-Drum Camera. Film speeds of 4–400 fps. Model 224 uses 35-mm film. Beckley & Whitley, Inc., 1093 San Carlos Ave., San Carlos, Calif. (photo).



Product Literature

Available free, unless otherwise stated, to those who request them on company letterhead

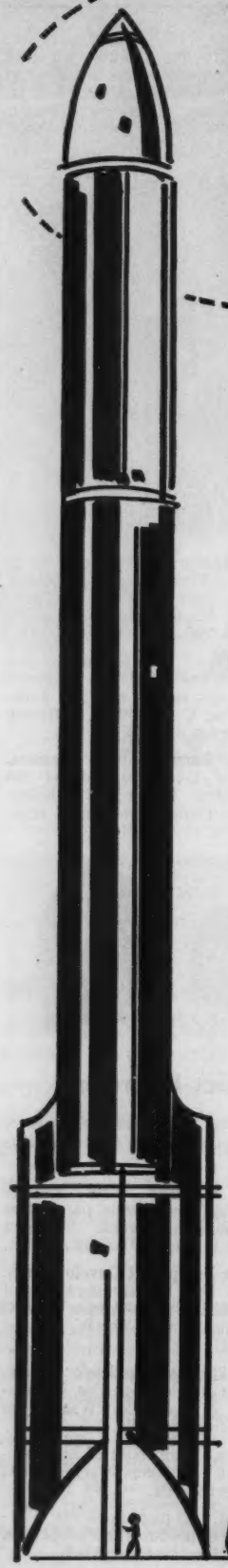
Handbook of Oven Facts. 19-page Bulletin no. 555 gives basic parameters in selecting industrial ovens. Michigan Oven Co., 415 Brainard, Detroit 1, Mich.

Industrial & Equipment Developments. January 1956 book covers control and testing equipment. Cole-Parmer Instrument & Equipment Co., 224 W. Illinois, Chicago 10, Ill.

Plexiglas. 75-page handbook for aircraft engineers details properties, installations. Rohm & Haas Co., Washington Square, Philadelphia 5, Pa.

Super Alloys. Properties of high-temperature alloys. Universal-Cyclops Steel Corp., Bridgeville, Pa.

Product List. 33-page book for 1955–1956 gives line of products and properties. Dow Chemical Co., Midland, Mich.



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Processes

Highly polished surfaces as used on high-speed jet aircraft and missiles can be protected during manufacturing operations such as drawing, blanking, drilling, routing, form rolling, riveting, etc. (photo). MetalGuard is a new strippable plastic coating developed by Guard Coatings Corp., 8-05 43rd Ave., Long Island City, N. Y. The plastic can be brushed, dipped, or sprayed on. Tensile strength is 2500 psi and elongation is up to 200%. The process allows pre-polishing of surfaces such as vitreous enamel, chrome, nickel, decorative laminates, and plated surfaces.

Chemical milling developed by North American Aviation Corp. has been carried to the production stage by the United States Chemical Milling Corp., 9999 W. Jefferson Blvd., Culver City, Calif. Complex patterns, small runs in the supersonic aircraft and guided missile field brought to light this new way of removing metal. Essentially, chemical milling is a controlled erosion. The metal is first masked, the desired design is scribed on the part, and then the mask on the area to be milled is removed. Etching solutions remove metal at a rate of about 0.001 in. per min with a tolerance of ±0.002. Fatigue tests show chemically milled aluminum sheets comparable to the original and machine milled specimens. This technique has also been applied to reducing weight on unmasked parts such as forgings, extrusions, and thick parts. Limiting factor for chemical milling now seems dependent only on the size of the tank used (photo).

A new machine by Stanat Manufacturing Co., 47-28 37th St., Long Island City 1, N. Y., now permits precision slitting of nickel and cobalt base alloys used in gas turbine engines. Both coil and sheets may be slit in widths of 8 in. and thicknesses of 0.01 to 0.003 in. Tolerances are ±0.001 in. (photo).

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By... NEWBROOK MACHINE CORP

SILVER CREEK, NEW YORK.

An effective combination of design, know how and precise workmanship have made available this linear actuator. This rugged, compact, dependable unit has proven able to perform under the most adverse conditions and temperature changes.

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As of press time for this issue

7,764

engineering and science students are slated to receive copies of the Special Supplement on

Careers in the Rocket and Missile Industry

To be published with the May, 1956, issue of

JET PROPULSION

The advance requests have been received from 148 professors and instructors who are members of ARS and/or active in some phase of research related to the rocket and missile field. They have volunteered to put the copies into the hands of those students who are considered to be potentially qualified for, and interested in, the field. Here is an accounting of the proposed distribution of the Supplement:

Students (through professors)	7,764
ARS members	4,200
Library subscribers to Jet Propulsion	1,200
Other subscribers	700
Additional requests anticipated	2,000
TOTAL DISTRIBUTION	15,864

Invitations to submit copy on careers available with their organizations have been sent to every company as well as university and government activity known to be working in some phase of the rocket and missile field. Instructions on copy preparation were included with these invitations.

Copy will be accepted until *April 2*. Space reservations, at regular advertising rates for JET PROPULSION, can be made through regional advertising representatives listed on page 137, or directly to Careers Supplement, JET PROPULSION, 500 Fifth Avenue, New York 36, N. Y.

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Mach number deviation indicator (2,726,545). Wm. D. Mullins, Jr., and Robert E. Smith, Downey, Calif., assignors to North American Aviation, Inc.

Measurement is made of deviations in the ratio of stagnation air pressure to static air pressure from a predetermined value. An electrical signal proportional to the deviation supplies a restoring torque.

Rocket motor (2,726,603). Wade H. James III, Stillwater, Okla.

Two-part rocket with separable rocket motor and containing an inert fluid in the warhead. A rupturable diaphragm separates tanks containing fluid oxidizer and fluid propellent fuel. Pressure is exerted by the fluid upon the oxidizer, and fuel expels them into the combustion chamber.

2,726,603

Axial compressor (2,726,806). Francis H. Keast, Toronto, Canada, assignor to A. V. Roe Canada, Ltd.

To impress air with desired flow characteristics upon finally leaving the compressor, the cross-sectional area of the annular passage diminishes progressively downstream. The area at the first stage diminishes at a rate less than the diminution rate at the last stage.

2,726,806

Reverse-flow vaporizer with single inlet and plural outlets (2,727,358). Leslie D. Howes, Nobel, Ontario, Canada, assignor to A. V. Roe Canada, Ltd.

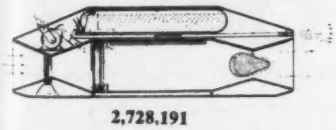
Conduit in a gas turbine engine combustion chamber, U-shaped in vertical section. One of its side walls is fluted longitudinally to provide alternated convex and concave surfaces facing the interior of the conduit.

Drag reduction in aircraft (2,727,706). Louis F. Heilig, Manhattan Beach, Calif., assignor to Northrop Aircraft, Inc.

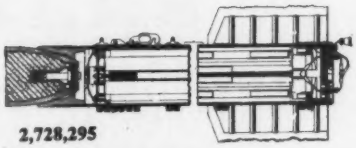
Wing leading edge with permanent and temporary portions forming a blunt leading edge for subsonic flight. At supersonic speed the temporary portion is separable from the permanent portion which has a sharp leading edge for supersonic flight.

Steam generation and auxiliary engines for ramjet engines (2,728,191). Hilton Wayne Casey, Chester, Pa.

Hermetically sealed tank adjacent the combustion chamber for holding confined water heated to its critical temperature. A valve controls the rearward discharge of water from the tank.



2,728,191



2,728,295

Multiple grain rocket (2,728,295). Sylvan Rubin, Wm. H. Corcoran, and Paul A. Longwell, Pasadena, Calif., assignors to the U. S. Navy.

Rocket motor with a compartmented open-side cage and having beveled corners defining valleys flaring toward the shell. A grid on one end of the shell has components fitting in the valleys.

Hydraulic drive powder catapult (2,728,538). Bernard Mazis, Woodbury Township, Gloucester, N. J.

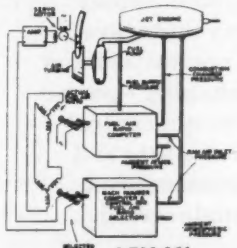
A U-tube with a piston moved by an explosion in one chamber and another piston in the other end, with liquid between. Air jets in the packing gland blast off the cable liquid that escaped the packing.

Continuous flow internal combustion engines, in particular aircraft engines (2,729,059). Claude Foure and Lucien Reingold, Paris, France, assignors to Office National d'Études et de Recherches Aéronautiques (ONERA).

Fuel injecting tubular element with outlets distributed throughout its length and opening at a substantial distance from the duct walls. Means for supplying fuel to the tube, and a flameholder within the duct downstream of the tube.

Fuel-air ratio control system for a ramjet engine (2,729,061). Louis N. Grafinger, Paramus, N. J., and Bernard J. O'Connor, Tuckahoe, N.Y., assignors to Bendix Aviation Corp.

Ratio computer sensitive to the fuel and air supply pressures, a Mach number computer and a fuel supply control. The control maintains the fuel-air ratio at a selected value changing the ratio to maintain the aircraft at a predetermined Mach number.



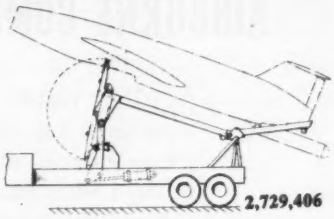
2,729,061

Combustion chamber for gas generation provided with cooling means, and a system for operating the same (2,728,192). Chandler C. Ross, Pasadena, Calif., assignor to Aerojet-General Corp.

Hydraulically operated system for controlling fuel flow of a gas turbine. A selective flow valve controls the direction of fluid from one side of a piston to the other. After pressure in the cooling liquid line has reached a predetermined value, the valve actuates automatically.

Zero-length launcher for aircraft (2,729,406). Orville J. Bush, Joppa, Md., assignor to The Glenn L. Martin Co.

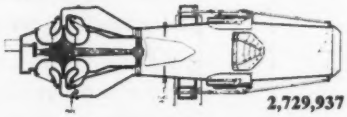
Bed carried on a frame for movement from a retracted to a launching position. An arm on the free end supports the front end of the aircraft. During launching, the arm swings forwardly and downwardly and a shock absorber on the frame limits swinging movement of the arm, preventing rebound into the path of the aircraft.



2,729,406

Aerodynamic aircraft brake (2,729,409). George J. Hand, Sr., Baltimore, Md., assignor to Decelo-Chute Corp.

A parachute with an automatic pilot chute attached contained in a storage tube, at the rear of the fuselage. A reel retrieves the control line extending through the tube to store the canopy within the tube.



2,729,937

Retractable flameholders for afterburners (2,729,937). George F. Hausmann, Windsor, Conn., assignor to United Aircraft Corp.

Flameholder comprising a segmental grid, each segment pivoted in the outer duct wall and forming a quarter of a flat circular grid. A motor moves the segments into the gas stream for operation, or retracts them into recesses in the outer wall.

Ribless pulse jet valve grid (2,729,939). Lawrence F. Campbell, Silver Spring, Md.

Pairs of metallic rectangular springs attached to the side of rods and mounted in a valve bank. Resilient members are sandwiched between each pair of springs.

Jet engine fuel control with stall computer (2,727,357). Edward J. Hazen, Woodcliff Lake, N.J., assignor to Bendix Aviation Corp.

Fuel supply operated in response to electrical signal voltage varying with changes in the prevailing air intake temperature.

Airplane design (176,604). Wendell B. Fehring, Wichita, Kans., assignor to Boeing Airplane Co.

176,604

EDITOR'S NOTE: The patents listed above were selected from recent issues of the Official Gazette of the U. S. Patent Office. Printed copies of patents may be obtained at a cost of 25 cents each, from the Commissioner of Patents, Washington 25, D. C.

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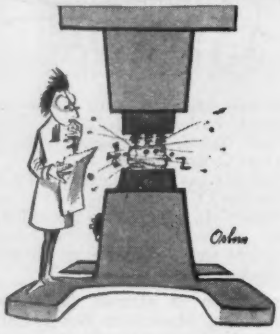

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Book Reviews

Ali Bulent Cambel, Northwestern University, *Associate Editor*

Advanced Mathematics for Engineers, by H. W. Reddick and F. H. Miller (third edition prepared by F. H. Miller), 584 pp., John Wiley & Sons, Inc., New York.

Reviewed by PATRICK BENSON
North American Aviation, Inc.

Because of the vigor and clarity of the authors' style, in addition to the applicability of the text and examples chosen, previous editions of this textbook performed an excellent job of introducing senior and first-year graduate students to advanced topics in mathematics. Casual inspection would not have revealed the need for a revision. Apparently, however, Dr. Miller had a clear enough view of the engineering field outside the walls of the school to see such a need and the revised book seems, all in all, to meet the requirements of today's students somewhat better.

The largest changes have been made in the problem sections where further problems were added and the average level of difficulty appears to be slightly higher. It was heartening to see that Dr. Miller has again included a complete list of answers, a practice which, unfortunately, appears to be falling out of favor.

Included also is a discussion of Legendre functions and an accompanying set of problems of a formal kind. Applications and problems dealing with applications are given in a revision of chap. VII which is devoted to some of the classical examples of mathematical physics. This reviewer feels that a brief treatment on orthogonality and orthogonal functions could have better integrated the discussion of Fourier Series, Legendre, and Bessel functions and possibly would have increased the value of the text as a reference in the student's later work.

The emphasis on today's needs is in evidence throughout. Whereas the second edition ended the discussion of Probability (chap. IX) with the method of least squares, the newer one includes a brief description of, and some problems on, the numerical methods for the solution of ordinary and partial differential equations.

In Chap. XI, dealing with Operational Calculus, a part was added treating Laplace transformations and their application in the solution of ordinary and partial differential equations. While the problems in this part were obviously designed to be solved without the use of the usual tables, this writer would suggest that the inclusion of tables of operational and functional transform pairs could have extended the usefulness of the book.

An introductory appendix on Dimensional Analysis, a useful engineering tool, has been added.

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accompany a course of instruction or for self-instruction. Therefore it was read with the student in mind, and this reviewer would unhesitatingly indorse it as a text for such purposes. There remains, however, the question of its utility to anyone engaged in a technical field who has progressed beyond such a course or to anyone interested in gaining additional knowledge of any of the particular subjects treated in the text. In this regard, it seems unlikely that this book would be any better than the introductory chapters of specialized texts.

The Lonely Sky, by William Bridgeman with Jacqueline Hazard, Henry Holt and Co., New York, 1955, 315 pp. $3.95.

Reviewed by C. F. WARNER
Purdue University

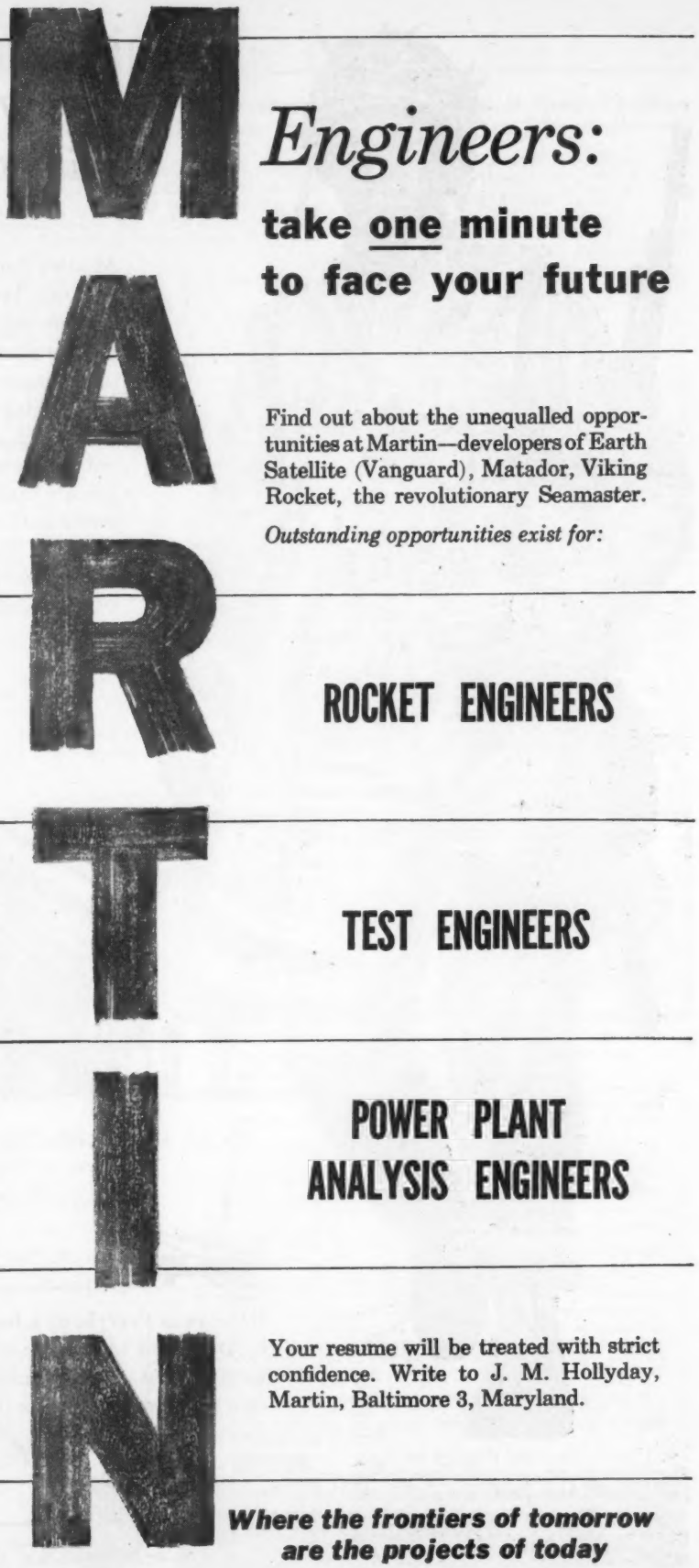
"The Lonely Sky" is the graphically told story of an experimental high speed airplane, the Skyrocket, and one of the test pilots who flew it. While much of the book may be classified as romantic, it does give a most interesting insight into the problems encountered in the testing of a rocket propelled aircraft at supersonic speeds. The first third of the book deals with William Bridgeman as a fighter pilot, his experiences during World War II, and his conversion into a test pilot of supersonic aircraft. The latter two thirds of the book give the reader the feeling of sitting beside Bridgeman as he puts the Skyrocket through its test flights culminating in the flight which established the world's altitude record.

The book is most enjoyable reading although it does not come up to the technical standards set by either "V-2" or "The Viking Rocket Story." Because "The Lonely Sky" does tell the story of the early flights of a piloted rocket propelled aircraft, this reviewer recommends the book to all "rocketeers" as fascinating reading for an evening's entertainment.

Flight Handbook, by the Staff of *Flight*, edited by M. A. Smith, Philosophical Library, Inc., New York, 1955, 282 pp. $6.

Reviewed by C. W. FILES
North American Aviation, Inc.

"It is the purpose of this new Flight Handbook to provide basic information on aeroplanes, their engines, and a great number of associated subjects." The above quotation from the foreword of Flight Handbook is a reasonable statement of the accomplishment of the editor in compiling this volume. Its nineteen chapters include a brief discussion of the atmosphere; a survey of aerodynamics for the layman; a historical outline of the development of aircraft structures; descriptive material on landing gear, controls, propellors, auxiliary power systems, instruments, cabin equipment, and armament; and a discussion of navigation systems. Seventy-five pages are devoted to engines and engine installation with some material on ramjets, rockets, and pulsejets. A total of approximately fifty pages are devoted to fixed-wing powered aircraft, rotorcraft, gliders and sailplanes, and balloons and airships.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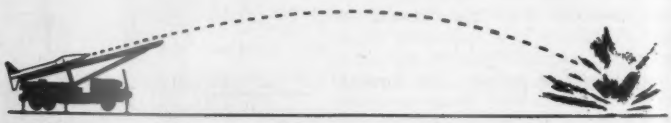

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Jet Propulsion Engines

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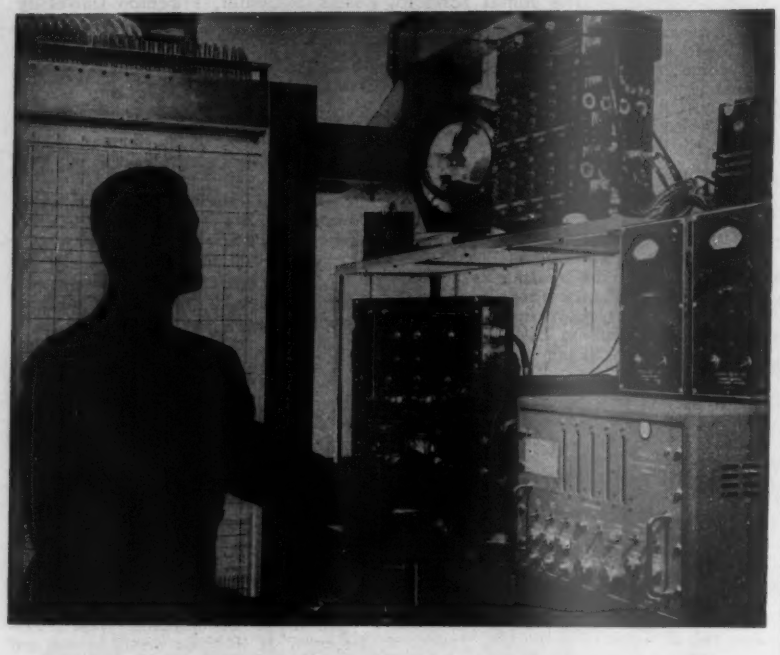

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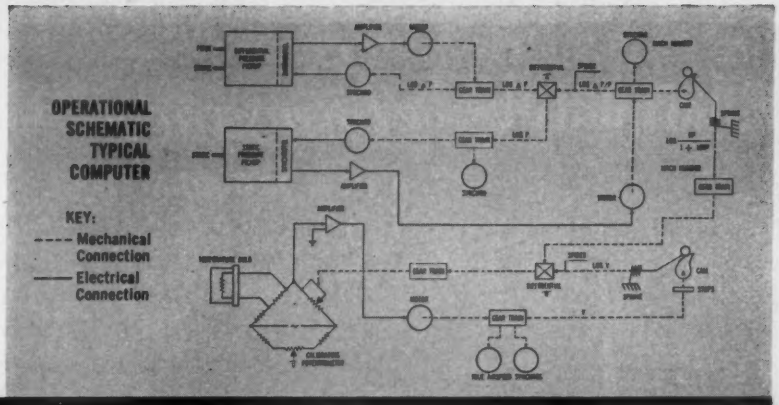

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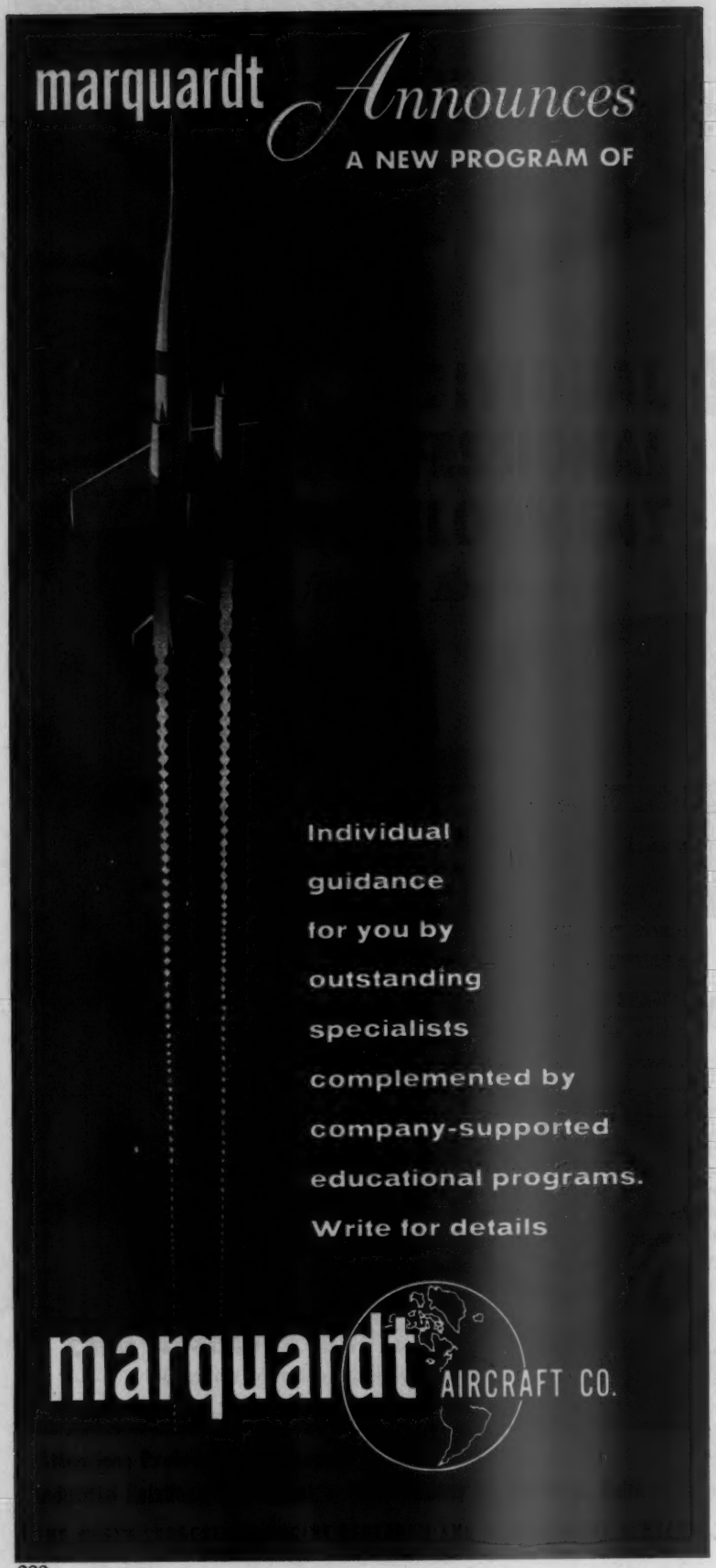

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